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MULTI-AGENT SYSTEM BASED MICROGRID CONTROL

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MULTI-AGENT SYSTEM BASED MICROGRID CONTROL

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ANIS SULAYMAN AMHARIB ISSA

ABSTRACT

Ph.D. Thesis

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Conventional power systems utilize a principal controller that collects entire system information for managing the network and decision making. The conventional power systems are normally renowned to be negative as power flows radially from the main grid to the loads. With the increasing permeation of distributed energy resources (DERs) at the power system level, the attention on the microgrid (MG) is increasing, the path of power flows inside the power network also changes. The MG is a new type of power system, which is formed by the interconnection of DERs, storage units and flexible loads. This type of power system allows power to flow from the main grid to the MG or vice versa. Accordingly, central control may be unable to efficiently manage and control many DERs, storage units and loads. Consequently, distributed control (decentralized control) is suggested instead of centralized control to overcome the problems of diversity in the sources of generation, loads, control and to exhibit the economic benefits at the MG level.

In this thesis, the multi-agent system (MAS) is suggested as a decentralized control system to manage and control microgrid. The prime notion is to use a MAS to resolve complex tasks where it will divide that tasks into small tasks assigned to several agents. A MAS is designed such that it shows intelligence and autonomous control with no direct intervention of a central control unit. Furthermore, a MAS is able to adapt to alterations in the environment and also it can adapt to any troubles or alterations in the power network.

The goal of this dissertation is to design and develop a MAS that allows real-time management of a MG. These involve the transition from grid-connected mode to an island mode seamlessly in the event of detecting main grid failure, protecting critical loads, implementing load shedding to maintain stability of the system and service restoration to grid-connected mode once the main grid voltage attains to the allowable value.

Also, a MAS has been used for optimizing microgrid power flow in both microgrid operation modes: the first one is an island mode. In this mode, the balance between generated power and demand for power should be achieved. The second mode is a grid-connected mode. This mode is implemented when the MG needs to purchase power from the main grid.

The proposed MAS has been developed in the JADE platform in order to manage and control a MG simulated in MATLAB/Simulink. Multi agent control simulation Jade extension (MACSimJX) toolkit as a middleware has been utilized in order to interchange data between MG in MATLAB/Simulink and MAS in the JADE platform.

The simulation outcomes show that suggested MASs promote the transition seamlessly from grid-connected mode to an island mode when the main grid failure is detected in addition to its capability to protect critical loads, perform load shedding for non-critical loads and service restoration. The simulation outcomes also illustrate the capability of a MAS to make a balance between generated power and demand for power with maximum efficiency and reduce fuel cost in two microgrid operation modes and during different dynamical loads.

Key Word : Microgrid, distributed energy resource, multi-agent system, MACSimJX and JADE.

Science Code : 90502

ÖZET

Doktora Tezi

ÇOKLU-ETMEN SİSTEM TABANLI MİKRO ŞEBEKE KONTROLÜ

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Geleneksel güç sistemleri, ağı yönetmek ve karar vermek için tüm sistem bilgilerini toplayan bir ana kontrol cihazı kullanır. Geleneksel güç sistemlerinde normal olarak güç, ana şebekeden yüklere radyal olarak akması nedeniyle negatif olduğu bilinmektedir. Dağıtılmış enerji kaynaklarının güç sistemi düzeyinde artmasıyla birlikte, mikro şebeke üzerindeki dikkat artmakta, güç ağının içindeki güç akışı yolu da değişmektedir. Mikro şebeke, mikro kaynaklar, yükler ve depolama cihazlarının birbirine bağlanmasıyla oluşturulan yeni bir güç sistemi türüdür. Bu tür güç sistemi gücün ana şebekeden mikro şebekeye veya tersi yönde akmasına izin verir. Buna göre, merkezi kontrol birçok dağıtılmış enerji kaynağını, yükü ve depolama birimini yönetemiyor ve kontrol edemiyor olabilir. Sonuç olarak, üretim ve yük kaynaklarındaki çeşitlilik sorunlarının üstesinden gelmek için merkezi kontrol yerine dağıtılmış kontrol (merkezi olmayan kontrol) önerilmektedir. Amaç, mikro şebeke faydalarını merkezi olmayan bir şekilde etkin yönetim ve kontrol ile arttırmanın mümkün olduğunu göstermektir.

Bu tezde, çoklu-etmen sistemi, mikro şebekenin yönetimi ve kontrolü için merkezi olmayan bir kontrol sistemi olarak önerilmektedir. Başlıca görüş, bu görevleri birkaç etmen devreden küçük görevlere bölerek, karmaşık görevleri çözmek için bir çoklu-etmen sistemi kullanmaktır. Çoklu-etmen sistemi, merkezi bir kontrol ünitesinin doğrudan müdahalesi olmadan istihbarat ve özerk kontrol gösterecek şekilde tasarlanmıştır. Ek olarak, çoklu-etmen sistemi, ortamdaki değişikliklere uyum sağlayabilmesinin yanında ayrıca ağdaki herhangi bir sorun veya değişikliklere de uyum sağlayabilir.

Bu tezin amacı, bir mikro şebekenin gerçek zamanlı yönetimine izin veren bir çoklu-etmen sistemi tasarlamak, geliştirmek ve yürütmektir. Bunlar, ana şebeke arızasının tespit edilmesi, kritik yüklerin korunması, kritik olmayan yükler için yük atma işlemin yapılması ve voltaj izin verilen değere ulaştığında şebekeye bağlı moda servis geri dönüşümü durumlarında şebekeye bağlı üsluptan adacık üslubuna sorunsuz bir şekilde geçişi içermektedir.

Ayrıca, her iki mikro şebeke çalışma üslupta mikro şebeke çalışmasını optimize etmek için bir çoklu-etmen sistemi kullanılmıştır: Birincisi bir adacık üsluptur. Bu üslupta, enerji üretimi ve enerji talebi arasındaki dengeye ulaşılmalıdır. İkinci üslup şebekeye bağlı bir üsluptur. Bu üslup, mikro şebekenin ana şebekeden güç alması gerektiği zamanda uygulanır.

Önerilen çoklu-etmen sistemi, JADE platformunda MATLAB/Simulink'te simüle edilmiş bir mikro şebekeyi yönetmek ve kontrol etmek için geliştirilmiştir. Çoklu-etmen tabanlı kontrol simülasyonu ara katman yazılımı olarak JADE genişleme araç seti (MACSimJX), MATLAB/Simulink'teki mikro şebeke ile JADE platformundaki çoklu-etmen sistemi arasında veri değişimi yapmak için kullanılmıştır.

Simülasyon sonuçları, önerilen çoklu-etmen sistemin, kritik yükleri koruma, kritik olmayan yükler ve servis restorasyonu için yük atma kabiliyetinin yanı sıra, ters akım kesintileri ortaya çıktığında şebeke bağlantılı üsluptan bir adacık üslubuna geçişi sorunsuz bir şekilde desteklediğini göstermektedir. Simülasyon sonuçları aynı zamanda çoklu-etmen sistemin farklı dinamik yükler sırasında iki mikro şebeke

çalışma üslubunda güç ve arz taleplerini maksimum verimlilikle sağlama ve yakıt maliyetini azaltma arasındaki dengeyi sağlama kabiliyetini göstermektedir.

Anahtar Kelimeler : Mikro şebeke, dağıtılmış enerji kaynakları, çoklu-etmen sistemi, MACSimJX, JADE.

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CONTENTS

Page

LIST OF FIGURES

Page

Page

LIST OF TABLES

Page

SYMBOLS AND ABBREVITIONS INDEX

SYMBOLS

P : active power

Q : reactive power

ip : the active current output of the converter

iq : the reactive current output of the converter

TR : transformer

ω : angular frequency

Ko : gain coefficient

I_{pv} : photovoltaic current

I_D : diode current

I_0 : reverse saturated current

k : Boltzmann constant

q : electron charge

C : capacitance

L : inductance

R : resistance

I : current

V : voltage

D : duty cycle

$V_{Battery}$: battery voltage

R_{in} : battery internal resistance

ø : leakage flux

$N1$: primary winding

$N2$: secondary winding

ABBREVIATIONS

MG : Microgrid
MAS : Multi-Agent System
DER : Distributed Energy Resource
MACSim JX : Multi agent control simulation Jade extension
FIPA : Foundation for Intelligent Physical Agents
GA : Generation Agent
LA : Load Agent
SCADA : Supervisory Control and Data Acquisition
DC : Direct Current
AC : Alternative Current
MPPT : Maximum Power Point Tracking
DOE : Department of Energy
CRS : Congressional Research Service
LV : Low Voltage
CHP : Combined Heat and Power
SS : Static Switch
EMS : Energy Management System
AGC : Automatic Generation Control
PCC : Point Common Coupling
DG : Distributed Generation
IGBT : Insulated-Gate Bipolar Transistor
SCR : Silicon Controlled Rectifier
PLL : Phase Locked Loop
AMS : Agent Management System
ACC : Agent Communication Channel
ACL : Agent Communication Language
DF : Directory Facilitator
AID : Agent Identifier
ATF : Agent Task Force

PV : Photovoltaic
GCM : Grid-Connected Mode
IM : Island mode
RGC : Restoring to Grid-Connected Mode
GUI : Graphical User Interface
KBU : Karabuk University

PART 1

INTRODUCTION

The increase in environmental consciousness and rising fuel prices have created an emerging trend of distributed energy resources (DERs) at the electrical distribution networks. DERs may be either sustainable energy resources or traditional units. DERs are typically used in applications that involve standby network support power and independent operation [1].

Moreover, in order to reduce consumers' carbon footprints, more attention has been given to the utilize of renewable technologies in recent years. All those reasons have stimulated considerable interest in microgrid research. With increasing of DERs penetration to power system, mostly to MV/LV distribution network power systems have to an active distribution system with involving consumers to take a point in management of power flow, etc [2,3]. The present power systems are expected to move from passive to more active power systems which will lead to difficulties in stability problems and managing power flow within the network [4,5]. Moreover, for the successful operation of microgrids, the integration of DERs has become an important side of other technical and operational difficulties faced [6].

If the central control approach is used in control active networks where there is bi-directionally power flow inside the network, difficulties may be faced. Although the central approach has been successful in managing traditional power systems operations. Centralized control of several distributed energy resources at distribution voltage levels can be problematic, as they are not feasible to implement economically, which requires other alternative strategies to the management of emerging DERs. A variety of distributed/decentralized approaches have been suggested to improve manage operations of the power system with the merging of a number of DERs at distribution voltage levels. It varies from hierarchical to a completely decentralized structure. Furthermore, the distributed/ decentralized approach adds many merits like future power system expansion potential, support for plug and play capabilities, increased system reliability, lower infrastructure costs, and reduced computational load on a central server. By this way, the decentralized approach is expected to overcome the limitations of the centralized approach and in the future adequately manage MG operations when more DERs are expected to merge with the current networks.

1.1. MOTIVATION OF THE THESIS

Conventional power systems generally allow power flows in one-way, and it accommodates just client loads but over the last few years, many reasons have urged experts to highlight microgrid schemes. Some motives, which encourage microgrids include:

- Reduction in carbon dioxide and other gaseous emissions.
- The efficiency of energy or using energy in a rational way.
- Cancellation of restrictions or policy of competition.
- Diversity in energy sources.

Microgrid integrates DERs, flexible loads and storage devices in a local distribution grid. Also, it operates in a grid-connected mode or in an island mode. The management of power and the available micro-sources' coordination control takes place through the microgrid.

Control and power flow management are needful to secure the stable and seamless operation of the MGs because of the expected increase in the penetration of DERs at the distribution networks level. Nevertheless, conventional centralized approaches for control proved to be insufficient to deal with the widespread of DERs because of the absence of expandability and flexibility [6]. Furthermore, central control was first used to manage and control large production units. But with a presence many of DERs in the power system, it is hard or almost not possible to manage and control the complete system by central control system [7,8]. If a central controller is executed, additional complexity will be introduced to the central control supervisor and it will need to increase costs for the communication substructure.

Likewise, as the energy industry moves towards decentralization, distribution networks and energy market operations are becoming increasingly complex [9]. Integrate DERs at the distribution voltage levels will cause the direction of the power flow inside the power system network to change from a passive to an active network. Thus, Supervisory Control and Data Acquisition (SCADA) which is a centralized control system was primarily designed for conventional networks, may be insufficient to deal with complex control decisions and the proliferation of distributed energy resources. Furthermore, the suppositions applied to traditional power systems may not apply to active distributed systems that increase the difficulties in the operation of the microgrids [10]. The main issues related to the merging of DERs are shown below [11,12].

- The need to send and schedule DERs under demand and supply uncertainties.
- Control and collaboration and which are achieved and distributed with minimum data exchange with the central control unit.
- Standards communication protocols like MACSimJX.

By providing a common communication interface to the agent platform in the distributed system, many of the above mentioned problems can be solved [13]. This can be accomplished by MAS, which is widely recommended as a convenient approach for controlling and managing distributed systems since it can more easily allocate complex tasks into simpler in order to perform its goals [14,15]. Applications of MAS in MG extend to include distributed generation control, coordination of control schemes, optimization microgrid operation, fault protection strategies and power flow management in real-time applications [16].

MAS is a decentralized form of control that displays distributed intelligence using software agents for communicating, negotiating, and optimizing microgrid operations. Unlike the centralized approach, MAS utilizes an ascendant approach to optimize and manage microgrid operations thus minimizing the communication and complexity of the microgrid. The main motivation to propose MAS in power systems is mainly due to its ingrained benefits, such as expandability, flexibility, autonomy, and other factors, as well as reducing the complexity of problems. Consequently, the motivation of the study is to design and develop an agent-based distributed control strategy to control and optimize microgrid operations.

1.2. THE PURPOSE OF THE THESIS

The purpose of this study is to design and develop multi-agent system based control of Karabuk university microgrid. To execute this purpose the following objectives are determined:

- Modeling and simulation Karabuk microgrid.
- Development of Multi-agent system (MAS) using JADE-platform in compliance with the specifications of the Foundation for Intelligent Physical Agents (FIPA).
- Design and development of the MAS architecture to control of Karabuk university microgrid.
- Protection and restoration of KBU MG based on MAS.
- Optimization of KBU MG based on MAS.
- Transmit control signals at a real-time to the DERs and loads for regulating their power set points.

1.3. METHODOLOGY OF THE THESIS

The focus of this dissertation is to design and develop MAS in the context of a MG. The developed MAS can perform the tasks of isolating the MG from main grid when the main grid failure is detected, protecting critical loads, implementing load shedding for non-critical loads, service restoration and optimizing the operation of a microgrid. The following tasks are carried out to fill in the knowledge gaps specified in the former paragraph:

- Identify the appropriate framework to build the agent.

- Design of the MAS architecture.
- Development of the MAS architecture.
- Connect of the microgrid simulation and the MAS architecture.
- Simulate agents' coordination and interaction based on different agents' targets.
- Transmit control signals at a real-time to the DERs and loads for regulating their power set points.

The MG is simulated in MATLAB/Simulink program and the MAS communicates with MATLAB / Simulink simulations via MACSimJX protocol. For assessing the performance of the agent-based control scheme for microgrids, the output active power, voltage and current waveforms for the loads and DERs will be analyzed.

1.4. LITERATURE REVIEW

According to experts, microgrids are increasingly becoming of the most significant power generation systems. It is a concept that merges several micro sources without letting the main grid operations disrupted. It is possible to connect the energy storage systems with either AC or DC microgrids. DC sources and loads are linked with DC networks, while the AC loads and sources are linked to the AC networks [17].

The electrical protection of the microgrid must be expanded to include both MG operation modes (grid-connected/ island modes). In case of a fault is detected in the main grid, the MG is isolated from the main grid, and must regulate its voltage and frequency, compensate the lost power for loads, especially for critical loads by distributed energy resources [18].

As a result of the huge development of the microgrids which contain a number of sensors and actuators associated with different devices within it to implement intelligent and autonomous decisions. The multi-agent system has drawn compelling attention in the current days on account of its ability to improve microgrid efficiency, decrease operation cost of generation units [19].

In Ref [20, 21], the authors describe the agent as an entity that can: take action in an environment, work with other agents to fulfill its goals, react to the changes in the environment. MAS consists of: an environment, objectives, agents, relations, which represent connections among agents and their objectives and operations, which are agents' tasks.

From Ref [22] we can understand the basic notions and properties of the entities which are associated with MAS, in addition, the possible merits of MAS in applications of power system.

According to Ref [23] the agent has been known as a software or entity that has the capability to perceive and interact with the changes in part of the environment by sensors and actuators.

In Ref [24], the authors describe the agent with several characteristics: autonomous- the capability to work with no direct intervention from human or devices, with specific control over its acts and decisions, social ability- the agents can communicate with humans and other agents by utilizing communication language to achieve their aims, reactivity- the agents can react to alterations in their environment at an appropriate time and pro-activeness- the agents have the initiative for exhibiting aims-oriented behavior.

The authors in Ref [25] submit the MAS as a group of agents that communicate with each other to resolve a complex problem in which a single agent can’t solve it. The authors classify MAS architecture as the following: centralized architecture, distributed architecture and hierarchical architecture. In a centralized structure, there is no communication between agents. A distributed structure consists of local agents are responsible for elements of the network. The local agents communicate with each other to detect the overall information of the system. In a hierarchical structure, some agents have power over the acts of other agents.

The authors in Ref [26, 27] classify the agents into two categories: reactive agents and cognitive agents. Cognitive agents are more intelligent and have communication abilities. Cognitive agents work as a central control unit that works with reactive agents and controls operations of non-critical loads. In case of a shortage of energy, the central control unit disconnects non-critical loads and reactive agents execute some operations that not require decisions from a central controller.

In Ref [28], the authors submit a distributed system of self-arranging. This distributed system consists of three agents are power agent, power storage agent and load agent. Each agent records and sends its capabilities to a directory, where other agents can assess and demand services. The load Agent is responsible for search about available agents of the power source and selecting offers for power supply. Power agents and power storage agents interact with each other to schedule storage cases.

In Ref [29], the authors implement a framework of MAS consists of 3 layers. The top layer agent oversees on power consumers and suppliers data and isolates loads in emergency cases. The agents in the middle layer adjust energy-producing sources in the system with the loads in batteries' status. The lower agent is responsible for the communication with the upper layer to receive the data table, orders to connect or isolate from the main grid as well as follow power data from the MG.

In Ref [30], the authors design a MAS framework that includes two levels (upper and lower level) where the agent in the upper level is in charge of providing the main substructure and services, the agents in the lower level are responsible for power supply and demand for power.

In Ref [31], the authors propose a MAS comprises of three agent control agent, distributed energy resource agent and load agent. The control agent is responsible for control a point common coupling (PCC). Distributed energy resource agent is in charge of interchange data among distributed generations such as communication status, power estimation and available energy sources. The load agent observes and controls the loads.

The authors in Ref [32, 33] use a multi-agent learning algorithm to promote the transition to the island mode. This algorithm uses the notion of layered learning. The notion of layered learning is utilized to collect orders and interactions of the agents according to their capability to change the environment and in the end the agents coordinate to achieve their aims.

In Ref [34], the authors propose an approach to manage and control the power of microgrid in real-time. This approach has been used to improve the operation of microgrid based on demand for power, fuel cost, gas emissions and loads.

In Ref [35], the authors propose a control algorithm contains a smart connection agent is utilized to isolate microgrid from the main grid smoothly. This is utilized to increase the microgrid efficiency in the case of transient voltages.

The authors in Ref [36] assign agents to generation units (GAs) and loads (LAs). LAs specify the unit price for the power needed. The task of GAs are selling the produced power at a price higher than the cost of production.

In Ref [37], the authors consider the conventional power system with a radial flow of power undergoes to the penetration of distributed energy resources that are very volatile, nonlinearities, dynamically changing and difficult to predict with certainly so the traditional protection schemes insufficient.

According to Ref [38] microgrid protection must cover both MG operation modes. when upstream blackouts are revealed, the MG is isolated from the main grid and must adjust its produced and consumed power, frequency and voltage to ensure stable operation.

In Ref [39], the authors develop A MAS comprises of three layers: recloser agents layer, zonal agents layer and switch agents layer. The three layers of agents interact with each other to determine and disconnect faults in a MG based on values and direction of the current during the fault. Recloser agents observe the case of reclosers at each substation. Each zonal agent has a switch agent associated with that zone. When a fault happens in the power system network, recloser agents send signals to zonal agents that are connected to switch agents. Each switch agent inspects its zone to isolate it in case of fault exist.

In Ref [40], the authors suggest a multi-agent system architecture that achieves a balance between the objectives of microgrid and demands. During normal operation of the microgrid, agents secure power flow for critical loads at all times in addition if there is extra power, they will export it to other microgrids. In an emergency case, the agents start to disconnect non-critical loads and request extra power.

The authors in Ref [41] submit a MAS architecture consists of three levels to overcome the permanent constraints of the microgrid (balance of active power and power flow). After a fault occurred, the agents in the lower and medium levels communicate with each other to calculate the available power and demand for power. The agents in the higher level supervise protocols of communication.

In Ref [42], the authors use wireless techniques to exchange information between agents inside the microgrid to service restoration to the grid-connected mode after the fault is cleared.

The authors in Ref [43] design a MAS where each agent is responsible for local knowledge for one node in the network and the agent can access the global information by local communication between agents. In this way, the agent is able to take synchronized load restoration decisions based on global information discovered by local communication between agents.

The authors in Ref [44, 45] develop a MAS controller for optimizing operations of the microgrid. The generations and loads in the microgrid are variety wherefore it is necessary, management these units efficiently to achieve the desired economic benefits from the microgrid.

In Ref [46], the authors use a MAS is capable to observe distributed energy resources and control power flow. The produced power is maximized based on the cost of production and distributed generation constraints.

1.4. THESIS STRUCTURE

This dissertation is structured in six chapters as follows. Chapter 1 presents an introduction to the microgrid. The motivation of the thesis, as well as objectives and methodology are also introduced. It also provides the literature review on applications of MASs in microgrid operations and the structure of the thesis.

Chapter 2 displays the microgrid definitions, microgrid reasons, benefits of a microgrid and components of the microgrid in detail. The operation modes of the microgrid, types of microgrid and control levels of AC microgrid are also presented.

Chapter 3 provides mathematical modeling of Karabuk University microgrid components included PV cell mathematical modeling, DC/DC boost converter, three-phase inverter, maximum power point tracking, battery, three-phase transformer and generator.

Chapter 4 submits a control and operation of microgrid based on MAS, microgrid control strategies and structure of the multi-agent system. It also presents applications of a multi-agent system in microgrid and multi-agent system benefits and constraints.

Chapter 5 provides a suggested MAS approaches for applications of MAS in a microgrid. The effectiveness of the proposed approaches was verified by case studies. The outcomes from case studies display the validation in employing a MAS to implement arranged and cooperated actions between its agents to achieve the desired aims of the system.

Chapter 6 offers a conclusion, contributions of this study and recommendations for future work on MASs researches in the context of distributed operations of the microgrid.

PART 2

MICROGRID OVERVIEW

According to experts, microgrids are increasingly becoming one of the most significant power production and management system for the future of the power systems. It is a concept that merges several micro sources without letting the main grid operations disrupted. It is possible to connect the energy storage systems with either AC or DC microgrids. DC sources and loads are linked with DC networks, while the AC loads and sources are linked to the AC networks [47].

2.1. MICROGRID DEFINITION

During the current period, many research organizations have presented several definitions of a microgrid in different reports. The following are some important descriptions of a microgrid:

The US Department of Energy has defined the MG as [48]:

A MG is a localized power network that integrates the distributed energy resources (DERs) with certain local flexible loads, which operate in a deliberate island mode or in parallel with the grid to offer high flexibility and reliability to face grid troubles. This integrated distribution system helps to address the power requirement in places with power supply and distribution limitations that mostly include remote sites.

The Microgrid has been defined by the Congressional Research Service (CRS) [49], and that definition is slightly different as compared to the one, which is given above:

Microgrids are local and small electric power systems, which work autonomously of the massive electric power network. It combines power and heating systems, which use natural gas combustion engine (that generates hot water, electrical power using the water), or fuel cells, diesel generators, or sustainable energy. Microgrids are used for fulfilling the electric supplies of research centers, data centers, plants, medical centers, military bases, and populations located in far-flung areas.

Another definition has been submitted by European research projects [50, 51]:

A Microgrid comprises low voltage (LV) distribution systems, which distribute energy resources (wind turbines, small generators, PV cells, etc.) in addition to storage units like batteries, flywheels, and supercapacitors as well as with elastic loads. Microgrid systems have two modes of operation in a non-autonomous way if connected to the main grid, or in an independent way if isolated from the grid. Integrate micro sources with the power network after coordinating their responsibilities can be boosted benefits to the whole system.

According to the previous definitions, the microgrid features include:

- Microgrid integrates DERs, flexible loads and storage devices in a local distribution grid.
- A microgrid can work in a grid-connected mode or in an island mode.
- The management of power and the available micro-sources’ coordination control takes place through the microgrid.

2.2. MICROGRIDS REASONS

Conventional large power grids offer several advantages. Huge generating stations are usually economical and not need a large number of human resources to its operated. The network of interconnected high voltage transmission allows reducing demand for generators. It is now possible to generate economical electricity and transport it to long distances with limited electrical line losses. A distribution network generally allows one-way power flows, and it accommodates just client loads but over the last few years, many reasons have urged experts to highlight microgrid schemes [52]. Some policy motives, which encourage microgrids include:

- Limitation of carbon dioxide and other gaseous emissions.
- The efficiency of energy or using energy in a rational way.
- Cancellation of restrictions or policy of competition.
- Diversity in energy sources.

Some other reasons have mentioned in Ref [53, 54] but with more emphasis on the following considerations:

- Modular generating plants' availability.
- Possibility to find locations for micro-generators.
- Limited building times and low cost of capital.
- The location of generating may be near to the load which may decrease transmission costs.
- Microgrids' technical influence on a distribution system.
- Changes in network voltage as well as regulation.

2.3. BASIC ARCHITECTURE OF MICROGRID

Figure 2.1 is illustrated structure of the microgrid system. It clearly indicates that a microgrid architecture comprises of distributed generation (DG) resource, distribution and storage systems, and control/communication systems [55].

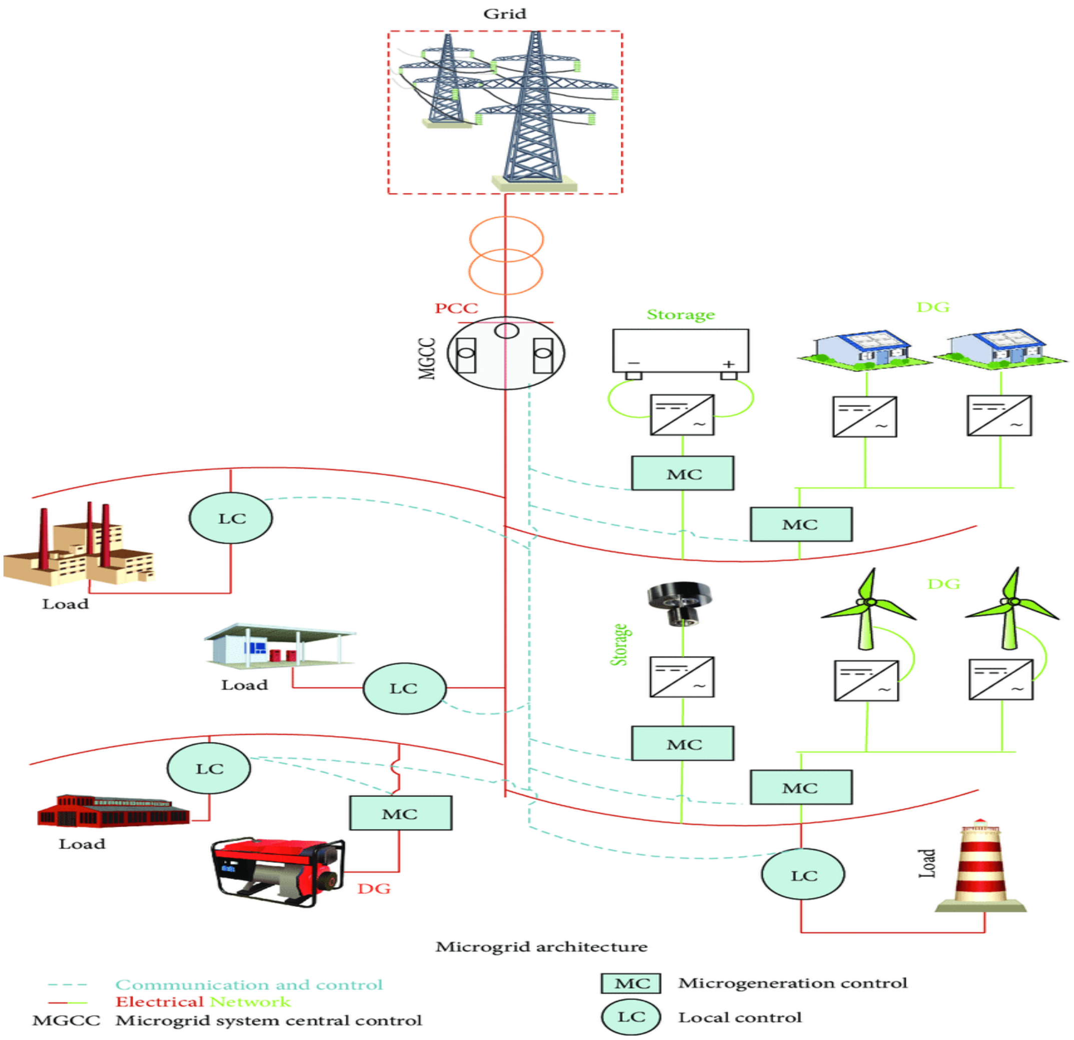

Figure 2.1. Example of MG structure [55].

2.3.1. Distributed Generation (DG) Sources

Numerous industrial technologies use renewable energy resources because it depends on non-depletable sources such as the wind, the light of the sun and underground heat.

Distributed generation systems, which are added to the microgrid, include certain emerging technologies including wind turbines, solar cells PVs, small hydropower generators, combined heat and power CHP and synchronous generators as well as single-phase and three-phase induction generators [56].

Distributed energy resources and storage devices consist of several modules can be installed in a brief time to become part of the power network.

Some typical characteristics of the DERs are shown in Table 2.1.

Table 2.1. DERs characteristics [57, 58].

CHARACTERISTICS	**WIND**	**PV CELL**	**MICROHYDRO**	**GENERATOR**	**CHP**
Possibility of Implementation	Depended on Geographical Location	Depended on Geographical Location	Depended on Geographical Location	At any Time	Based on Source
Output of Power	AC	DC	AC	AC	AC
Gaseous Emissions	None	None	None	High	Based on Source
Possibility of Control	Not Controllable	Not Controllable	Not Controllable	Controllable	Based on Source
Interface	AC-DC-AC Converters	DC-AC-DC Converters	Induction Generator	None	Synchronous Generator

2.3.2. Storage Systems

The effective operation for microgrid requires to add storage units to achieve a power balance between generated power and demand for power in the short-term. Lasseter [28] concluded in his research that the system that has many DERs, which are designed for operation in the island mode, must have some storage devices for assuring the energy balance. Microturbines and fuel cells have large time constants perform within the 10-200s range so storage systems are significant for power balance after large load changes or system disturbance [59]. When sudden changes take place in the system, the storage devices can work as sources of AC voltage by using inverters. Since they have physical limitations, their capacity for energy storage is limited. The backup energy-storage apparatuses must be added to the microgrid system because they give numerous merits such as improvement of power quality, smoothing the sustainable power resource’s discontinuity, assure a continuous supply of power, and empowering auxiliary services such as regulation of voltage and frequency in operation of microgrid. Some appropriate storage devices, which can be added to a microgrid system, are flywheels, batteries, and super capacitors [38].

2.3.3. Distribution Network Systems

There are three classes of a distribution network in a microgrid [60]:

- DC Line: Majority of the DERs generate DC voltage; so, they have no power quality issues, investigation on DC microgrid system is gaining more significance. However, most of the loads are AC loads; therefore, the DC distribution systems are still not common yet.
- 50/60 AC Line: Can be called line frequency. Most of the microgrids are line-frequency microgrids. The DERs are linked in the microgrid to a common bus. The DC current emerging from distributed energy resources is sent to 50Hz AC through an appropriate inverter and then sent to the load side.
- High Frequency AC (HFAC): Several methods are available for connecting DERs in a microgrid system. Utilizing HFAC for transferring energy in the microgrid is still a new concept and it is still in the development stage. The DERs are linked in a common bus in HFAC microgrids. The DERs' power generation transforms into AC 500Hz through power electronics devices and is sent to the load side, where an AC/AC converter again converts it into 50Hz AC. This load is linked to the distribution network, which results in effective interaction between the distribution network and the microgrid. The harmonics of higher order are filtered at a higher frequency, which limits the active and reactive power problems. HFAC has some issues such as it increases power losses and raises line reactance [60].

2.3.4. Loads

The loads represent the components which consume power including lighting devices, gadgets, industrial loads, and commercial equipment, etc. Loads in microgrid can be categorized into critical and non-critical loads. Critical loads represent loads in which power must be saved with high goodness and dependability, and so cannot be disconnected while non-critical loads represent loads which can be disconnected from power supply for specified time periods to keep up the microgrid working conditions.

2.3.5. Point Common Coupling (PCC)

This point exists in the electric circuit, in which, a MG is linked with the main grid. MGs without a PCC are termed as “confined” MGs because they have remote mechanical destinations. In this case, the interconnection with a primary network is impossible out of technological or financial reasons [61].

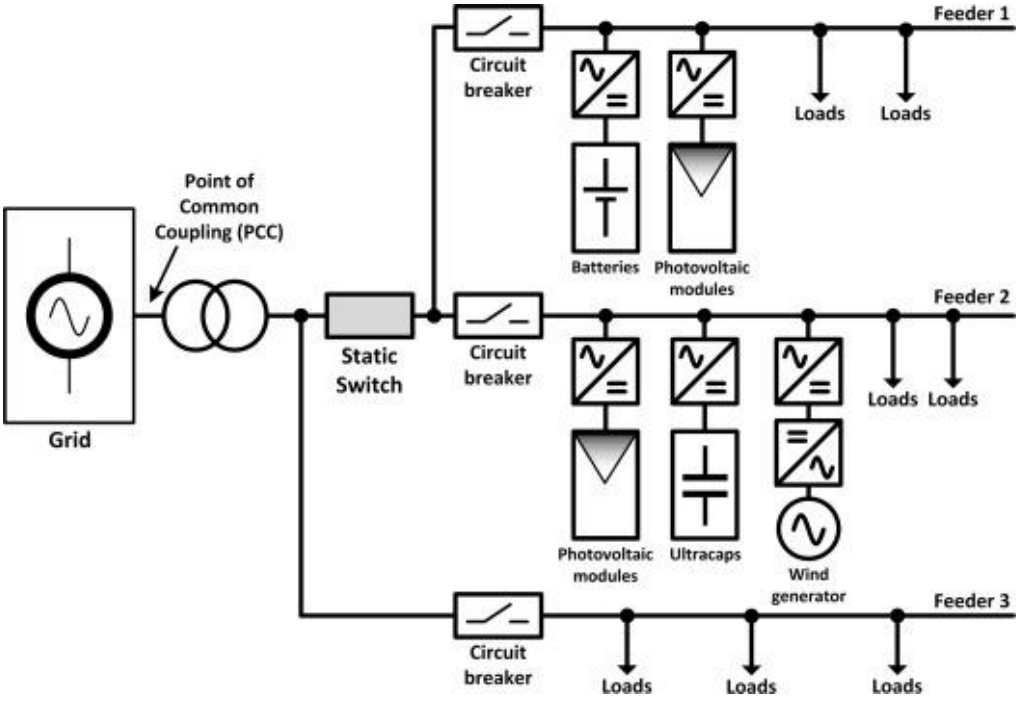

Figure 2.2. Location of point common coupling (PCC) [62].

2.3.6. Static Switch (SS)

The static switch links the MG to the main grid.

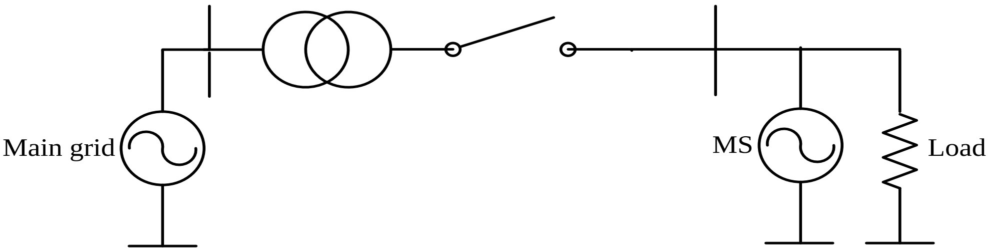

Figure 2.3. A static switch and microgrid scheme [63].

Protection of microgrid by isolating it from the main grid during emergency or maintenance cases is one of the important issues in microgrid applications. The static switch enables the microgrid of connection and disconnection with the main grid.

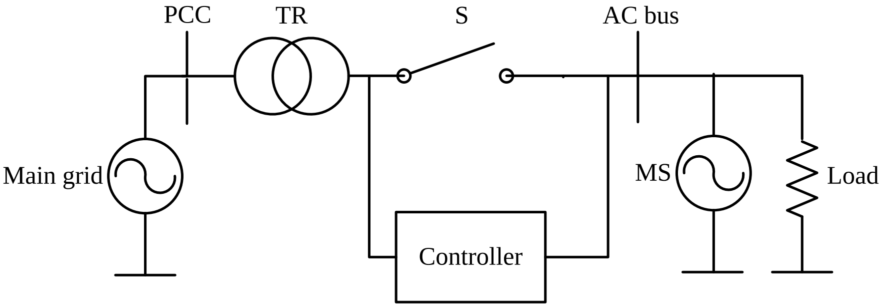

Figure 2.4. A static switch consists [63].

2.3.7. Systems of Communication

Systems of communication are very significant in the control and protection of power systems. The methods of basic communication, which are used in the existing microgrid testbeds, include broadband over power line, power-line carrier, lines of telephone, LAN/WAN/Internet (TCP/IP), global system for mobile (GSM) communication, optic fiber, wireless radio communication, WiMAX, Wi-Fi, and ZigBee/IEEE 802.15.4 [56].

2.4. MICROGRID OPERATION MODES

The microgrid operation modes are as follows [64]:

- Grid-connected mode: In this mode, a microgrid is linked with the main grid at the point of common coupling. In this mode, the MG receives its partial or total energy from the main grid based on power-sharing. In the case of surplus power, the surplus is sent to the main grid.
- Island mode: This mode is executed when the main grid failure occurs, or when there are some routine procedures such as maintenance, the microgrid can

transition to island mode seamlessly; therefore, the microgrid becomes autonomous; so, it is called island mode.

2.5. MG TYPES

Experts have classified microgrids based on operational modes, types, source, scenario and sizes, figure 2.5 illustrated that [65, 66].

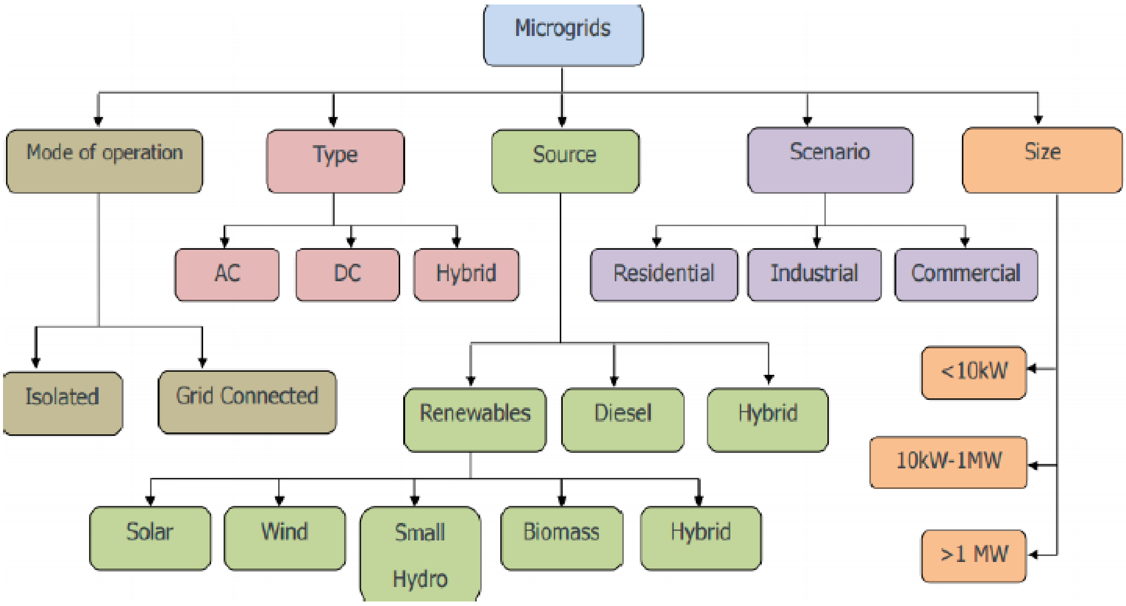

Figure 2.5. Microgrid classification [65] .

Based on the type of power, MGs are classified into:

- DC microgrids.
- AC microgrids.
- Hybrid AC and DC coupled microgrid.

2.5.1. DC Microgrid

DC microgrids have a DC bus that supplies the connected DC loads. Generally, DC loads are electronic devices with low power consumption including mobile phones, computers, wireless phones, battery-powered electric sweepers, video players, and internet devices. The sources which have DC output are directly linked to DC bus, while the sources which have AC output, are linked with the DC bus by AC/DC converter. Advantages of DC microgrids are as follows:

- Few frequency components, which simplify control.
- For DC loads not need to AC/DC converter where they can be integrated directly with DC sources thus reducing costs and energy dissipation.
- Less line losses in the DC transmission lines in comparison with the AC transmission.
- Low cost.

The issues of the DC microgrids are as follows:

- Difficult expansion.
- Electrical arc is very dangerous during DC breaking.

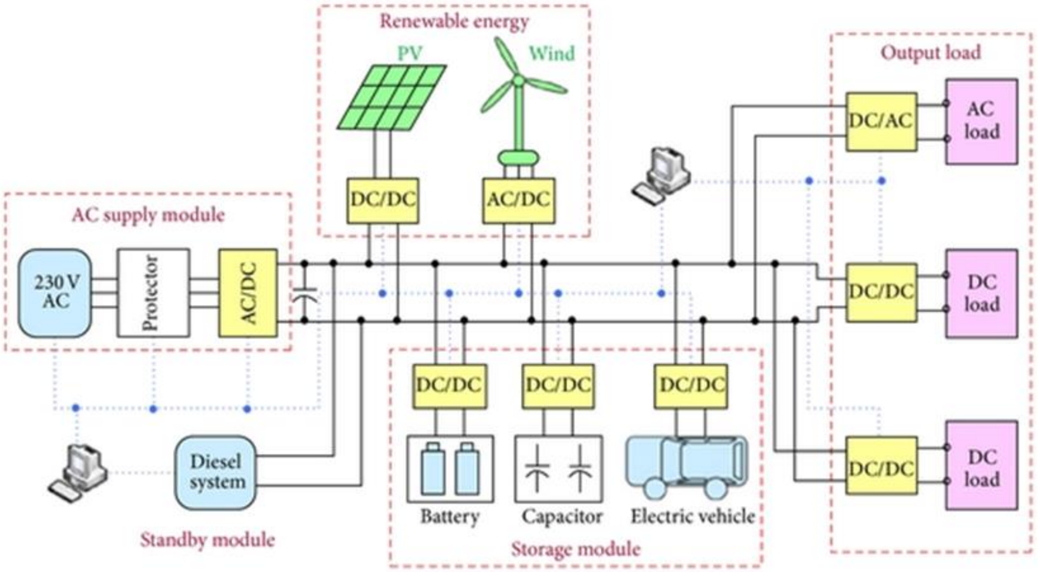

Figure 2.6. Scheme of a DC microgrid [67].

2.5.2. AC Microgrid

All parts in the AC microgrid system are linked with standard AC voltage of the grid (such as 50Hz, 230/240V) at a point before the local load. This system has the merit of expandability. This type of power system is now popular because it has decentralized power networks. The principal disadvantage for these systems is they need an inverter [68].

The advantages of AC microgrids are:

- The dump load (it is an electrical device to store power in case the batteries get full or whenever extra power is no longer needed) is not needed when it is linked to the grid.
- It is easier to expand.
- Circuits are simple.

The AC microgrids have the following disadvantages:

- It is required DC/AC inverters which are expensive.
- Inverter makes it less efficient.

Mostly in distribution system AC microgrid is used. The construction of AC microgrid is obvious in Figure 2.7. In AC microgrids, power storage units and distributed energy resources are linked with an AC bus by power electronics devices. The static switch is used as a control to switch mode from the grid-connected mode to islanded mode and vice versa [69].

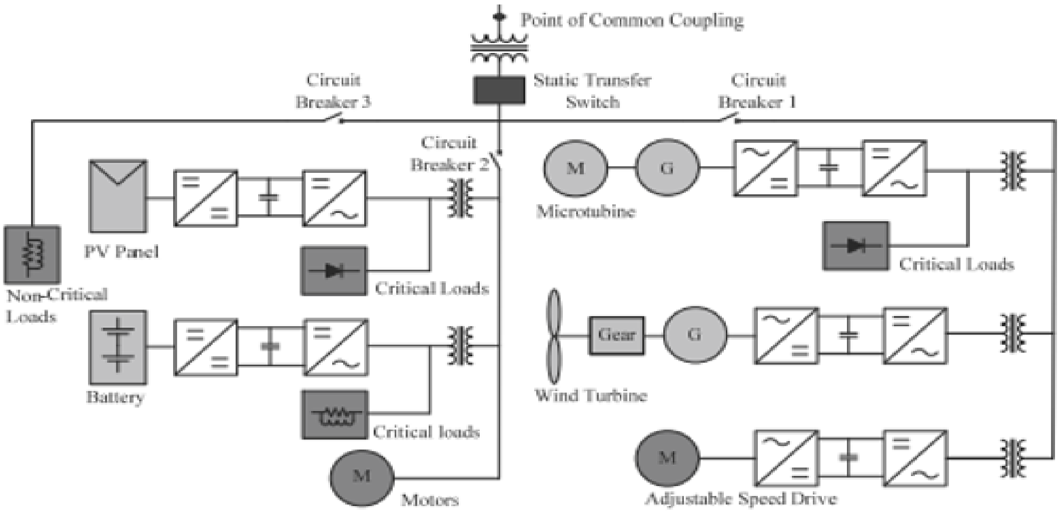

Figure 2.7. AC microgrid system [68].

2.5.3. Hybrid AC/DC Microgrid

Experts believe that the hybrid system is a futuristic substitution to the conventional power system that assures the power reliability, store energy and save operational costs because this system merges different renewable energy resources AC and DC.

The hybrid microgrids include the AC and DC MGs features, and both are interconnected to each other by electronic devices (converters). AC DERs and loads are linked to the AC bus whereas DC DERs and loads are linked to the DC bus. Storage units are either connected to the DC or the AC bus. The AC microgrid is connected to the main grid in the normal mode, in which, the main grid supplies power to the whole system and keeps stabilization it. In the islanded mode, a static switch disconnects the AC microgrid from the main grid. All the storage devices and distributed energy resources are installed with a purpose to stabilize the system [70].

An exemplary construction of a hybrid AC/DC MG has been clarified in Figure 2.8, which shows a couple of grids including an AC and a DC grid and both are connected to each other via a bidirectional AC/DC converter. The three-phase AC grid is connected with the main grid by step down transformer and circuit breaker. Both AC loads and AC DERs are linked with the AC grid while the DC DERs are linked with the DC grid by converters. DC storage units and loads are connected to a DC grid by DC/DC converters [71].

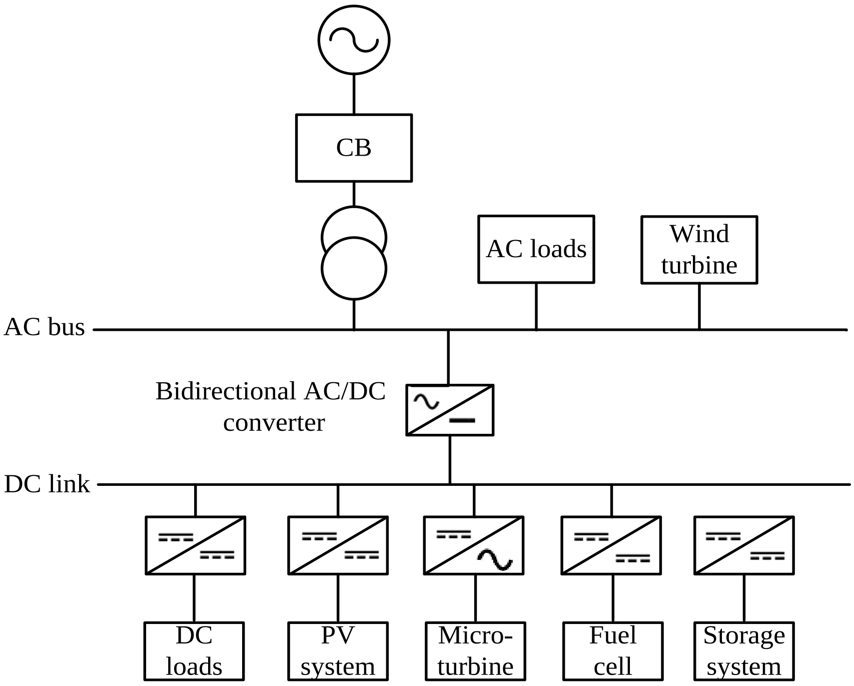

Figure 2.8. Hybrid microgrid system.

2.6. OBJECTIVES OF CONTROL IN AC MICROGRIDS

Microgrids either operate in the island or the grid-connected mode. The suitable control in a microgrid assures economical and stable operation. The microgrid control structure has certain principal roles, which are mentioned below [64, 72-76]:

- Frequency and voltage regulation in both the operating modes.
- Appropriate distributed energy resources coordination and load sharing.
- Resynchronizing a MG with the main grid.
- Management power flow between the microgrid and the main grid.
- Optimizing the operational cost of a microgrid.
- Suitable dealing during transient periods and restoration of operational conditions when transitioning between modes.

2.7. CONTROL LEVELS OF AC MICROGRID

The demands that we mentioned in the above paragraph have varying significances; therefore, they require a hierarchical control structure for addressing every requirement at different hierarchical control levels. The hierarchical control levels of a microgrid are primary, secondary, and tertiary controls, which have been exhibited in Figure 2.9.

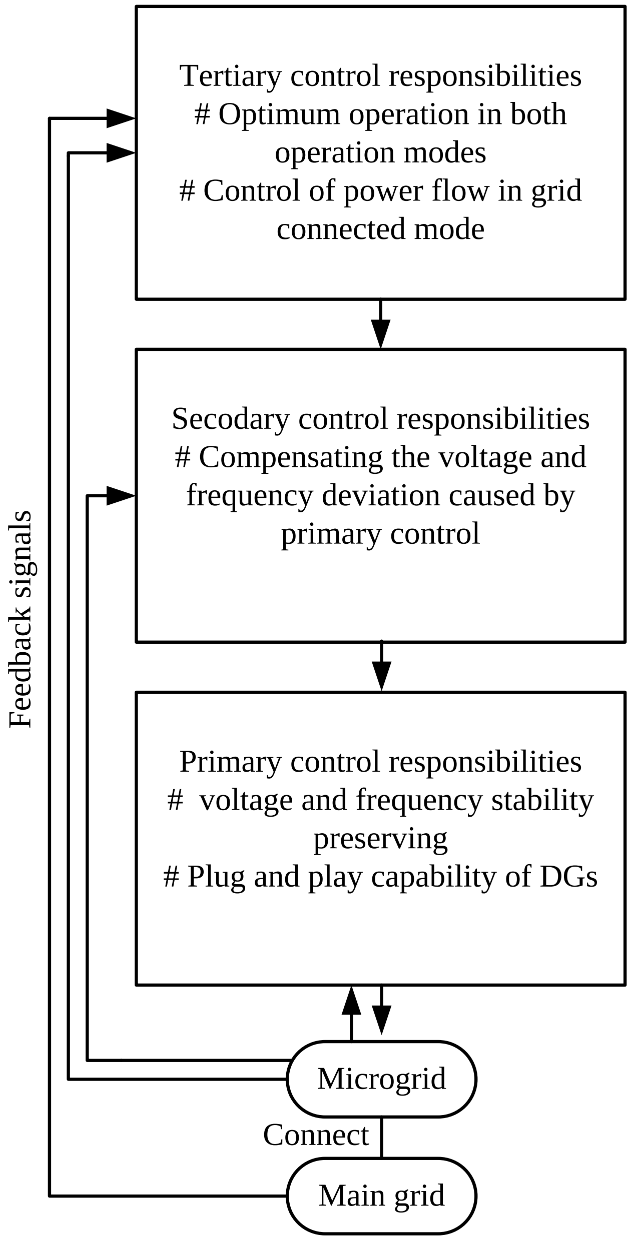

Figure 2.9. Hierarchical control levels of a microgrid.

2.7.1. Primary Control Level in AC Microgrid

The primary control or the local control level offers the setpoints for control loops (voltage and current) of distributed energy resources.

The purpose of the primary control level includes the following:

- To ensure frequency and voltage stability: Right after an islanding event, a microgrid is likely to lose its voltage and frequency stability because there is a mismatch between power generation and consumption.
- To provide a plug-and-play capability for distributed energy resources and implement power-sharing among them, which happens without any communication link.
- Mitigating circulating currents: Sometimes, two power sources have different voltages, which are connected in parallel, and it is connected to a load in parallel combination. Circulating currents result in overcurrent in the power electronic devices, which may damage the DC-link capacitors.

The primary control level offers the reference points for the current and voltage at real-time of distributed energy resources through active/reactive (PQ) power control mode or voltage control mode. PQ control mode regulates the active and reactive distributed energy resources power delivery in the pre-determined reference points, which are given in Figure 2.10. In this figure we show that H_1 control unit regulates the active power and the DC-link voltage through control the magnitude of the active current output of the converter (i_p). H_2 control unit adjusts the reactive power output through magnitude control in the reactive current output (i_q) [72].

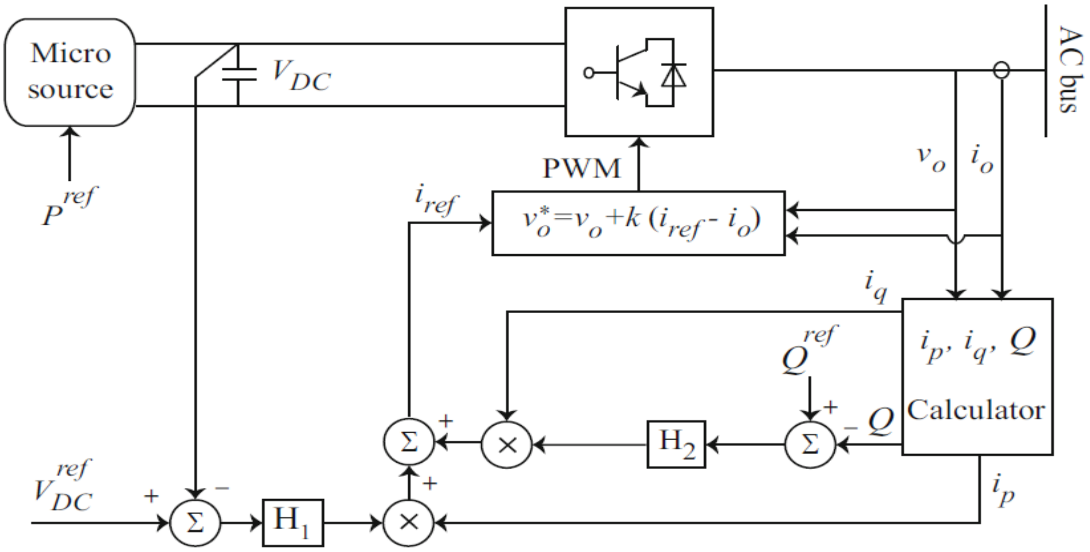

Figure 2.10. PQ control mode with active and reactive power references [72].

Figure 2.11 shows the voltage control mode that includes the voltage and current control loops.

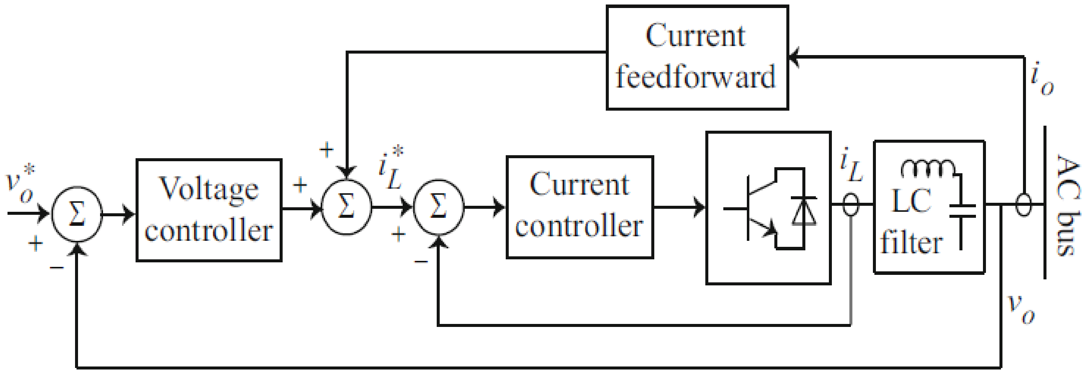

Figure 2.11. Voltage and current control loops in voltage control mode [72].

$$v_0^*(s) - v_0(s) = v_e(s) \tag{2.1}$$

$$i_L^*(s) - i_L(s) = i_e(s) \tag{2.2}$$

2.7.2 Secondary Control

The primary control level might result in voltage and frequency deviations. Despite the fact that the energy storage units compensate for the mentioned deviations, they cannot supply power for controlling the load frequency in the long term because of their limited energy capacity. The primary control level is locally implemented at each distributed energy resource. The centralized secondary control restores the frequency and voltage of the microgrid and recompenses the deviations that occur due to primary control [72].

Figure 2.12 illustrates the block diagram of the traditional secondary controls with a centralized structure. As the figure indicates, the microgrid frequency and the terminal voltage of a selected distributed energy resource are compared to their corresponding reference values such as ω_{ref} and V_{ref}. The individual controllers process error signals, which are given in Equations 2.3, 2.4; so, the resulting signals ($\delta\omega$ and δE) are transmitted towards the primary control unit of the distributed energy resource for compensating for the voltage and frequency deviations [72, 77].

$$\delta\omega = K_{Pw}\left(\omega_{ref} - \omega\right) + K_{I\omega}\int\left(\omega_{ref} - \omega\right)dt + \Delta\omega_s \tag{2.3}$$

$$\delta E = K_{PE}\left(V_{ref} - E\right) + K_{IE}\int\left(V_{ref} - E\right)dt \tag{2.4}$$

K_{Pw}, $K_{I\omega}$, K_{PE}, and K_{IE} represent the controller parameters. An additional term, $\Delta\omega_s$ to smooth synchronization of the microgrid with the main gird. $\Delta\omega_s = 0$ in island mode. During the synchronization, a phase-locked loop PLL module calculates $\Delta\omega_s$.

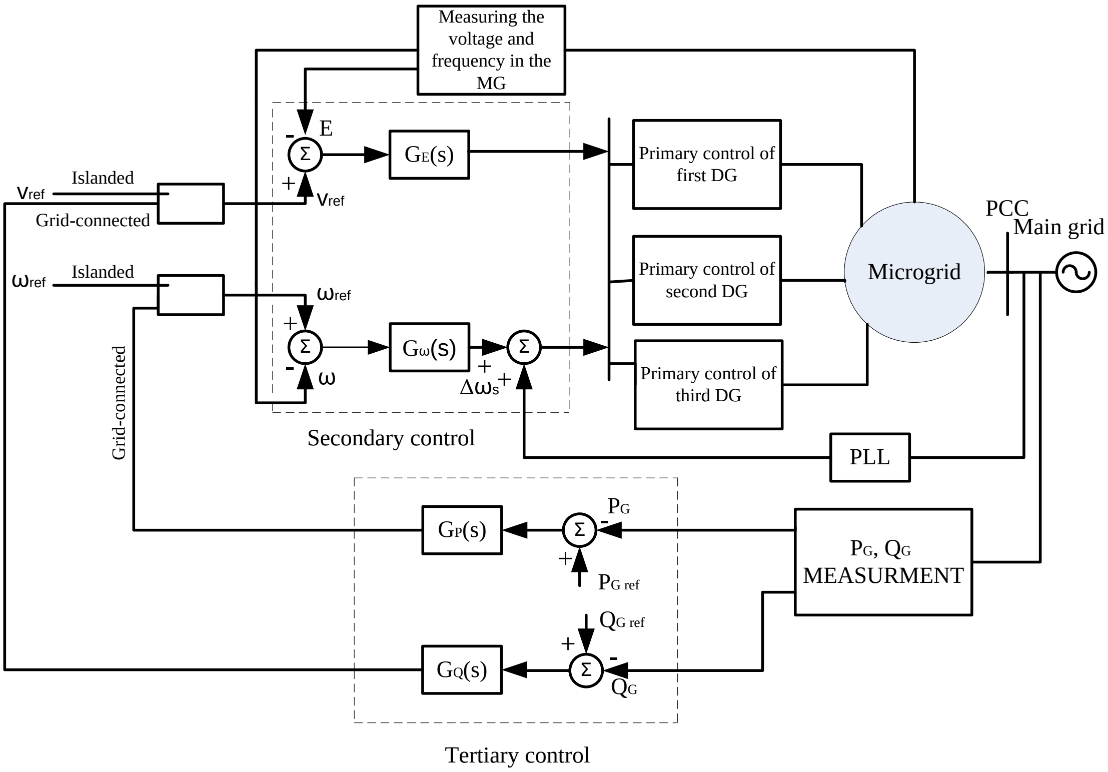

Figure 2.12. Secondary and tertiary controls [72].

Figure 2.13 demonstrates PLL block diagram. Where, the phase comparator/detector creates the phase for every input that generates an error signal $V_e(t)$, which is proportional to the phase differences between two inputs. In this case, K_D represents the gain of the phase detector (v/rad).

$$V_e(t) = K_D\left(\emptyset_{out}(t)-\emptyset_{in}(t)\right) \tag{2.5}$$

The low-pass filter deletes high frequency. The voltage is controlled through oscillation frequency. It is compared to the input frequency and controlled until it equal to the input frequencies.

$$\omega_{out} = \omega_o + K_o V_{cont} \tag{2.6}$$

Here ω_o represents nominal angular frequency, and K_o is a gain coefficient $(rad/s/v)$.

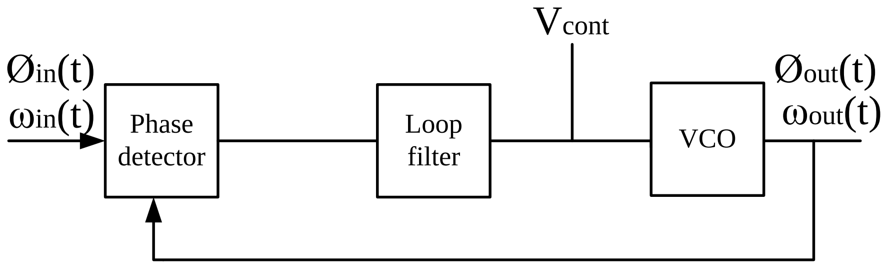

Figure 2.13. Block diagram of PLL [78].

2.7.3 Tertiary Control

The economic operation of the MG and managing power flow among the main grid and MG are responsibilities this level [79]. Grid-connected mode allows the power flow among the main grid and the MG by controlling the frequency and voltage of distributed energy resources. This process is illustrated in Figure 2.12. The measurements of both active and reactive output powers were done for microgrids P_G and Q_G. The mentioned quantities are previously compared to the corresponding reference values, $Pref_G$ and $Qref_G$, to get the reference for frequency and voltage, ω_{ref} and v_{ref} based on the following Equations:

$$\omega_{ref} = K_{pp}(Pref_G - P_G) + K_{IP}\int (Pref_G - P_G)\, dt \tag{2.7}$$

$$v_{ref} = K_{pq}(Qref_G - Q_G) + K_{Iq}\int (Qref_G - Q_G)\, dt \tag{2.8}$$

Here, K_{pp}, K_{IP}, K_{pq}, and K_{Iq} are controller parameters [72]; ω_{ref} and v_{ref} are applied later as the reference values for the secondary control, which is obvious from Equations 2.3 and 2.4.

PART 3

MATHEMATICAL MODELING OF ENGINEERING FACULTY KARABUK UNIVERSITY MICROGRID COMPONENTS

In our work Karabuk University (KBU) campus microgrid is considered as studied research object. KBU consists of eight faculty buildings in the campus. Nowadays, five of eight buildings are installed PV-arrays. For our case study we are selected one building- Engineering faculty.

A distribution network of Engineering faculty of Karabuk University consists of two micro sources (PV panels and generator), interface to connect the PV panels to the network (boost converter, maximum power point tracking (MPPT), batteries and inverter), from the main grid side a step-down transformer. this network also contains three loads, two of them are critical loads and the other is non-critical loads. More details about Karabuk University's microgrid components will be discussed in the following chapters of this thesis.

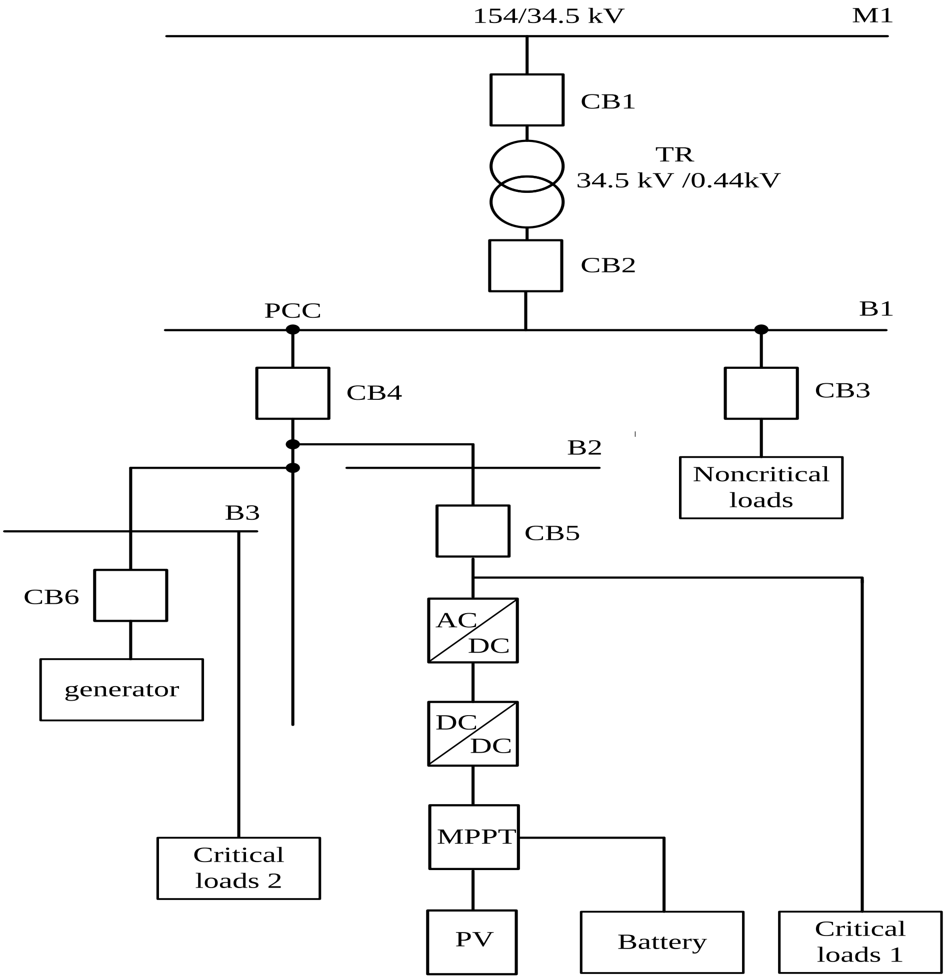

Figure 3.1. Architecture of Engineering Faculty of Karabuk University (KBU) microgrid.

3.1. MATHEMATICAL MODELING OF PV CELL

The equivalent circuit of solar cell consists of source of current in parallel with a diode. But actually, there is no ideal solar cell, thus a parallel resistance and series resistance are appended to the model as shown in Figure 3.2 [80].

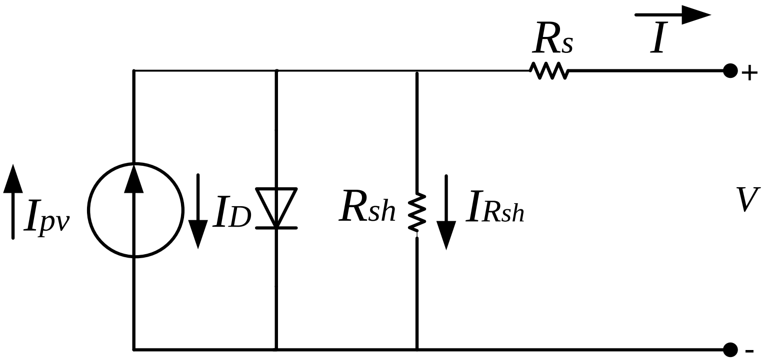

Figure 3.2. Solar cell equivalent circuit [16].

$$I = I_{pv} - I_D - I_{R_{sh}} \tag{3.1}$$

$$I_D = I_0 \left(e^{\frac{qv_d}{kT}} - 1 \right) \tag{3.2}$$

I_o = reverse saturated current.

$$I = I_{pv} - I_0 \left(e^{\frac{qv_d}{kT}} - 1 \right) - \frac{v_d}{R_{sh}} \tag{3.3}$$

We have:

$$-v_d + IR_s + V = 0 \tag{3.4}$$

$$v_d = IR_s + V \tag{3.5}$$

$$I = I_{pv} - I_0 \left(e^{\frac{qv_d}{kT}} - 1 \right) - \left(\frac{IR_s + V}{R_{sh}} \right) \tag{3.6}$$

k = Constant of Boltzmann = $1.381 * 10^{-23} \ \frac{J}{K}$.

q = charge of an electron = $1.60217662 * 10^{-19} \ C$.

3.2. BOOST CONVERTER MATHEMATICAL MODELING

A boost converter (DC/DC) uses to raise PV cell voltage. The main circuit of boost converter consists of inductor, electronic switch, diode, capacity element and load as shown in Figure 3.3 [81-83].

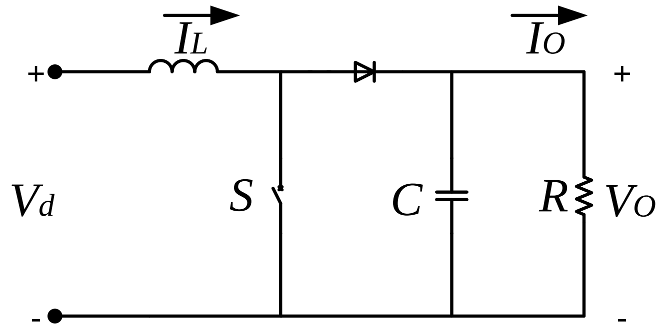

Figure 3.3. Equivalent circuit of boost converter.

When the switch is turn-on the boost converter equivalent circuit becomes as Figure 3.4.

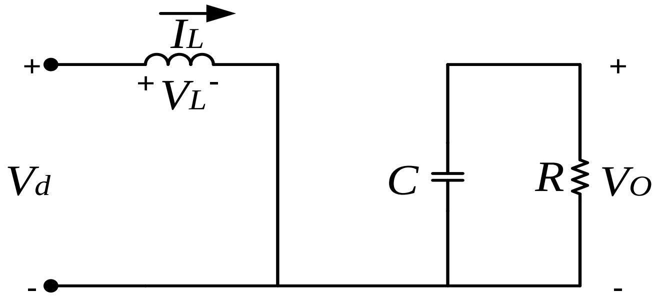

Figure 3.4. Boost converter circuit when the switch is a turn-on.

$$V_L(t) = V_d \tag{3.7}$$

$$\frac{di(t)}{dt} = \frac{V_d}{L} \tag{3.8}$$

$$T = t_{on} + t_{off} \tag{3.9}$$

$$\Delta i_{on} = t_{on} * \frac{V_d}{L} \tag{3.10}$$

$$Duty\ cycle\ (D)\% = \frac{t_{on}}{T} * 100 \tag{3.11}$$

$$\Delta i_{on} = D * T * \frac{V_d}{L} \tag{3.12}$$

When the switch is turn-off the boost converter equivalent circuit becomes as Figure 3.5.

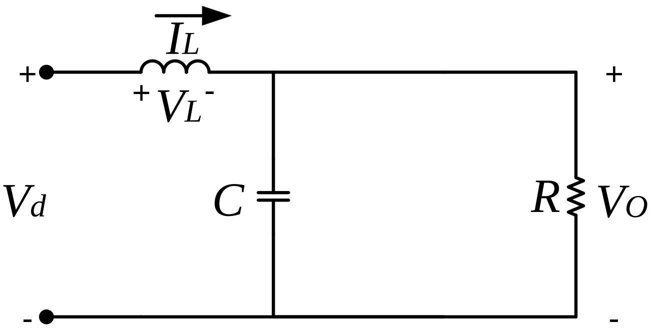

Figure 3.5. Boost converter circuit when the switch is a turn-off.

$$V_L = V_d - V_o \tag{3.13}$$

$$\frac{di(t)}{dt} = \frac{V_d - V_o}{L} \tag{3.14}$$

$$\Delta i_{off} = (T - t_{on}) * \frac{V_d - V_o}{L} \tag{3.15}$$

$$\Delta i_{off} = (T - TD) * \frac{V_d - V_o}{L} \tag{3.16}$$

At steady state

$$\Delta i_{on} + \Delta i_{off} = 0 \tag{3.17}$$

$$D * T * \frac{V_d}{L} + (T - TD) * \frac{V_d - V_o}{L} = 0 \tag{3.18}$$

$$V_o = \frac{V_d}{1 - D}, D < 1 \tag{3.19}$$

3.3. MATHEMATICAL MODELING OF MAXIMUM POWER TRACKING

MPPT is a common technique uses to improve the efficiency of PV cells under all conditions. Many techniques are used to track the MPP like perturb and observe, incremental conductance method, fractional short circuit current, fractional open circuit voltage, neural networks and fuzzy logic. In PV systems the most commonly used techniques to track the MPP are incremental conductance and perturb and observe [84].

3.3.1. Incremental Conductance Technique

This technique uses two sensors at the output terminal of the PV system one to measure voltage and the other to measure the current. The output voltage is controlled based on the MPP voltage. Figure 3.6 shows the incremental conductance technique on a P-V curve of solar module. The derivative of power to the derivative of voltage $\left(\frac{dP}{dV}\right)$ is zero at MPP. On the left side of the MPP the $\frac{dP}{dV} > 0$ and on the right side of the MPP the $\frac{dP}{dV} < 0$.

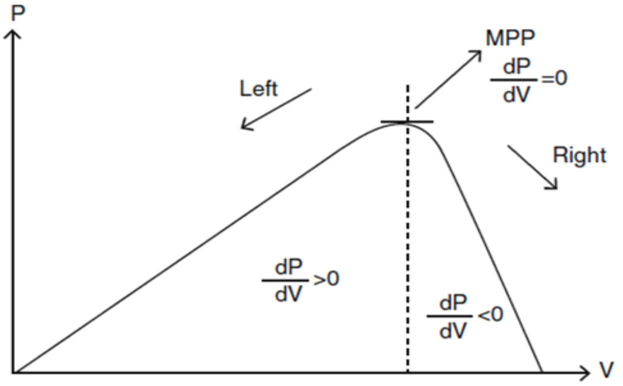

Figure 3.6. Incremental conductance technique on a P-V curve of solar module.

The main formulations of this technique are as per the following:

$$P = VI \tag{3.20}$$

$$\frac{dP}{dV} = \frac{dVI}{dV} \tag{3.21}$$

$$\frac{dP}{dV} = I + V\frac{dI}{dV} \tag{3.22}$$

At MPP $\frac{dP}{dV} = 0$

$\frac{dI}{dV} = -\frac{I}{V}$ at the MPP

$\frac{dI}{dV} > -\frac{I}{V}$ at the left side of the MPP

$\frac{dI}{dV} < -\frac{I}{V}$ at the right side of the MPP [85].

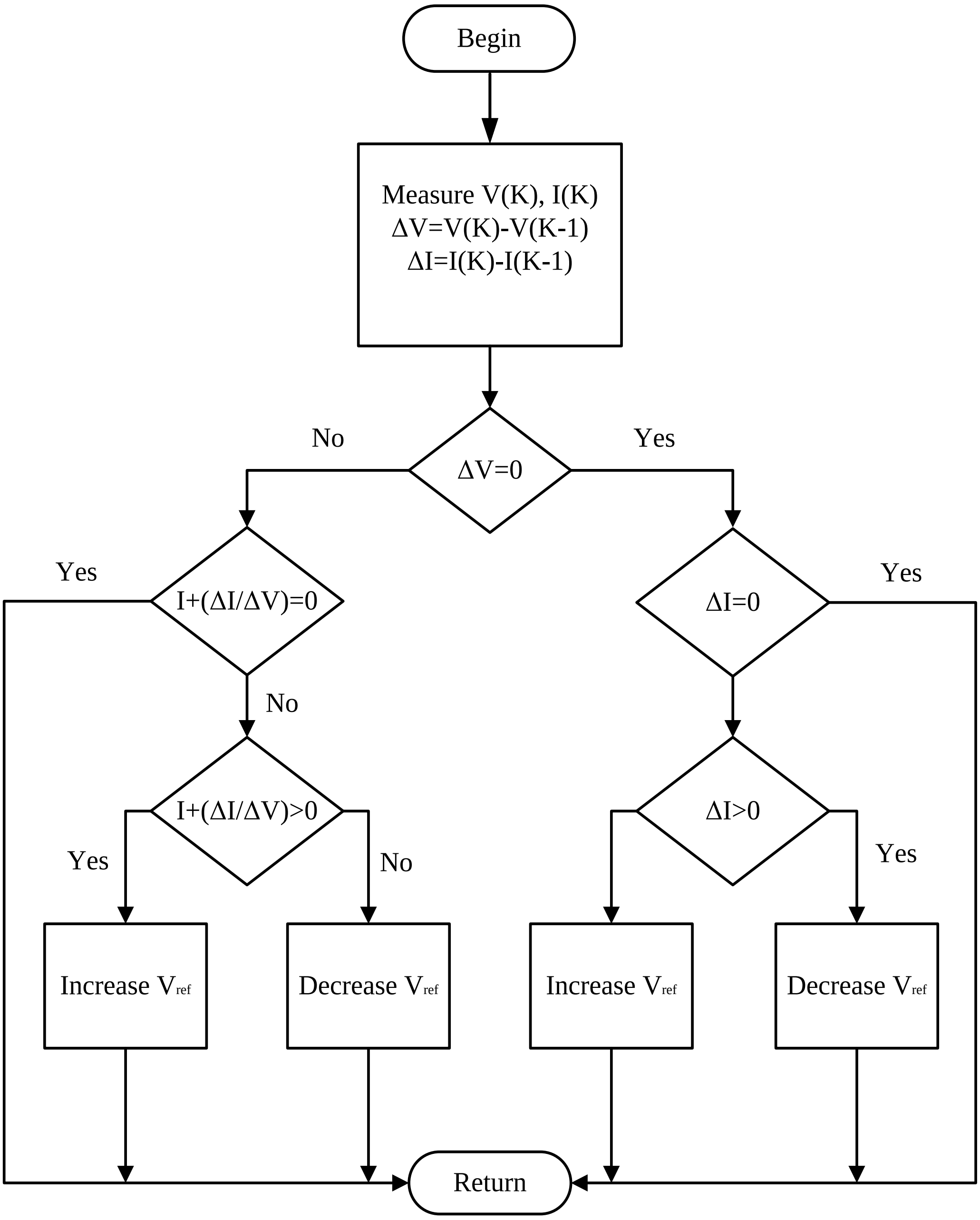

Figure 3.7. A flow chart of an incremental algorithm.

3.3.2. Perturb and Observe Technique

The most generally used MPPT algorithm is a perturb and observe method and is also called a hill-climbing algorithm. As shown in Figure 3.8 this technique uses a feedback arrangement where uses a fixed step size to obtain the MPP. When the sign of increasing power start to be negative, the tracking will be in the reverse direction and should return one step back [86].

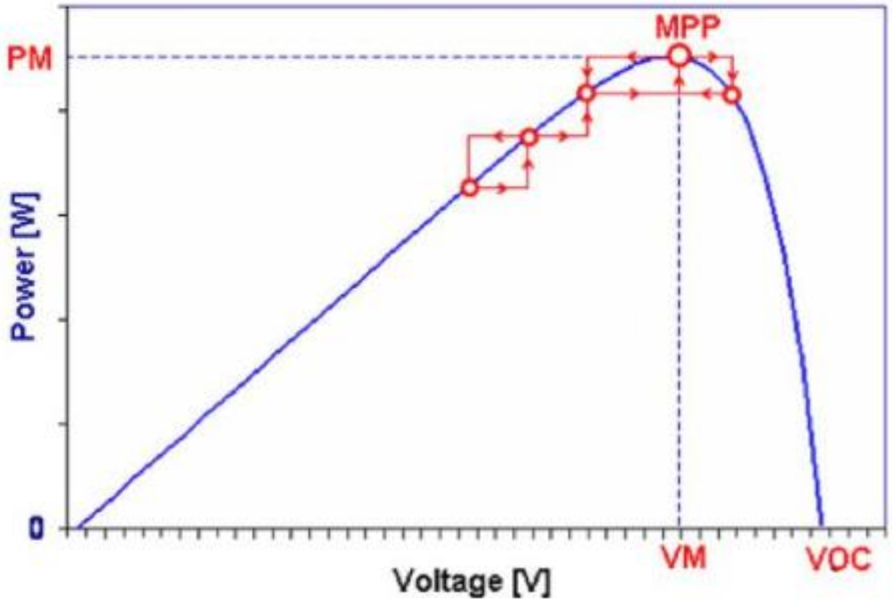

Figure 3.8. Perturb and observe technique.

The flowchart of perturb and observe algorithm is shown in Figure 3.9.

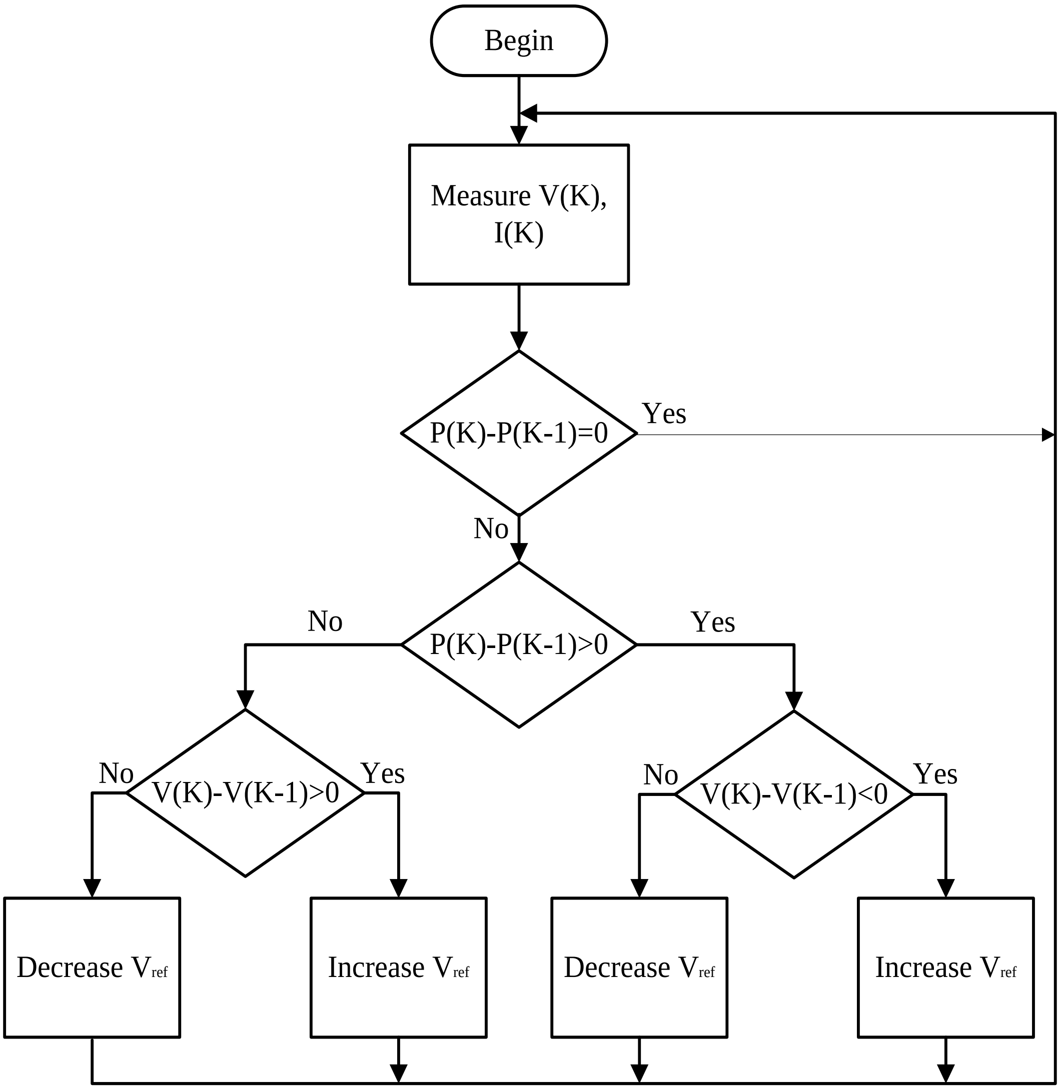

Figure 3.9. Perturb and observe flowchart.

3.4. MATHEMATICAL MODELING OF THREE PHASE INVERTER

In microgrids, the three-phase inverter is used to connect DC bus to the AC grid. The intent of the inverter is to convert DC into AC voltage in real-time. The three-phase inverter consists of three branches. Each branch contains two switches usually are IGBTs or MOSFETs and two diodes. The diodes are connected to the IGBTs in reverse ward biasing to path the reverse current in case of the inductive load [87, 88].

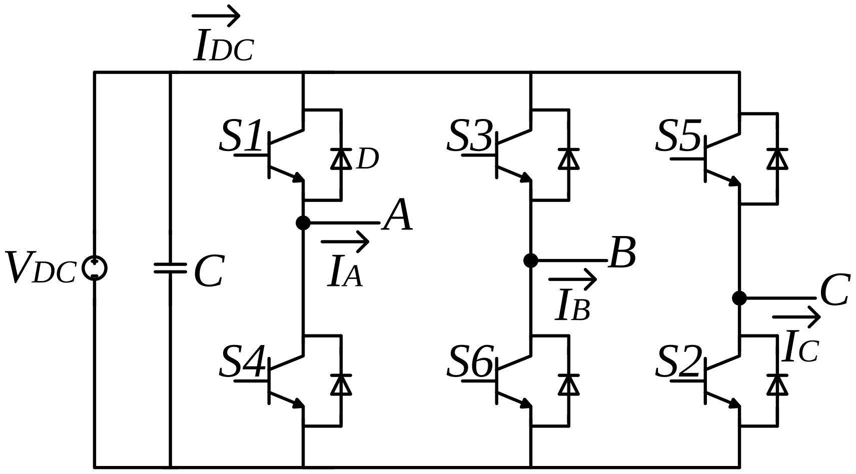

Figure 3.10. Equivalent circuit of three-phase inverter.

$$I_{DC} = S_a I_A + S_b I_B + S_c I_C \tag{3.23}$$

$$V_{AB} = (S_a - S_b)V_{DC} \tag{3.24}$$

$$V_{BC} = (S_b - S_c)V_{DC} \tag{3.25}$$

$$V_{CA} = (S_c - S_a)V_{DC} \tag{3.26}$$

Whereas S_a, S_b, S_c ϵ [0,1], which are zero when the lower switch in the branch is closed and one when the upper switch in the branch is closed [89].

3.5. MATHEMATICAL MODELING OF BATTERY

Battery equation can be characterized by the controlled voltage source:

$$E = E_0 - K\frac{Q}{Q - \int idt} + Aexp\left(-B\int idt\right) \tag{3.27}$$

$$V_{Battery} = E - R_{in} I_{Battery} \tag{3.28}$$

Where: E_0 is the voltage of battery without load (V),K is the voltage of polarization (V), Q is the capacity of battery (Ah),A is the amplitude of exponential zone (V), B is the time constant inverse of the exponential zone $(Ah)^{-1}$, $V_{Battery}$ is the voltage of battery (V), R_{in} is the internal resistance of battery (Ω), $\int idt$ is the current of battery (A) [90].

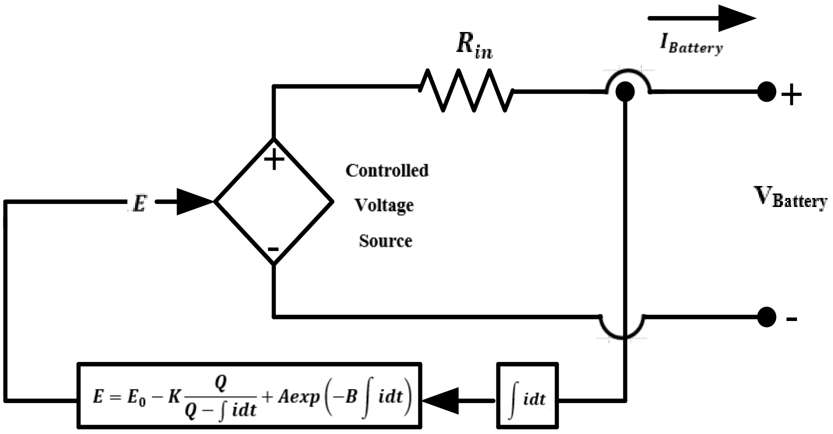

Figure 3.11. Modeling of a battery [90].

3.6. MATHEMATICAL MODELING OF TRANSFORMER

Figure 3.12 shows the magnetic field which is coupled among the primary and secondary windings of the transformer.

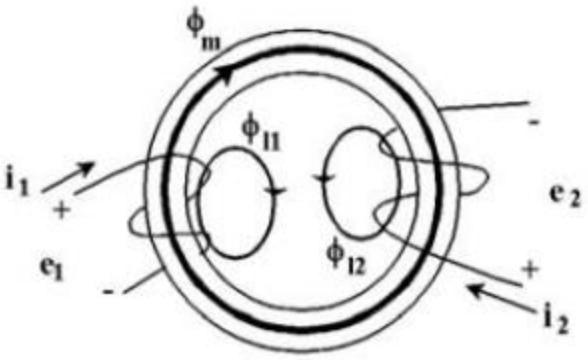

Figure 3.12. Two winding of transformer [91].

$$ø_{L1} = \frac{\lambda_{L1}}{N1} \tag{3.29}$$

$$ø_2 = ø_{L2} + ø_m \tag{3.30}$$

Where $ø_{L1}$ and $ø_{L2}$ are the equivalent leakage flux for *N1* and *N2* windings. λ_{L1} and λ_{L2} are the primary and secondary leakage flux linkages. $ø_m$ the equivalent mutual flux linking.

$$ø_1 = ø_{L1} + ø_m \tag{3.31}$$

$$ø_2 = ø_{L2} + ø_m \tag{3.32}$$

The primary and secondary terminals voltages are:

$$e_1 = R_1 i_1 + N1\frac{dø_1}{dt} = R_1 i_1 + N1\frac{dø_{L1}}{dt} + N1\frac{dø_m}{dt} \tag{3.33}$$

$$e_2 = R_2 i_2 + N2\frac{dø_2}{dt} = R_2 i_2 + N2\frac{dø_{L2}}{dt} + N2\frac{dø_m}{dt} \tag{3.34}$$

We have:

$$\lambda_{L1} = N1ø_{L1} \tag{3.35}$$

$$\lambda_{L2} = N2ø_{L2} \tag{3.36}$$

And from equations 3.35 and 3.36 the primary and secondary leakage inductances are:

$$L_{L1} = \frac{\lambda_{L1}}{i_1} \tag{3.37}$$

$$L_{L2} = \frac{\lambda_{L2}}{i_2} \tag{3.38}$$

So that:

$$L_{L1}i_1 = \lambda_{L1} = N1\o_{L1} \tag{3.39}$$

$$L_{L2}i_2 = \lambda_{L2} = N2\o_{L2} \tag{3.40}$$

And

$$L_{L1}\frac{di_1}{dt} = N1\frac{d\o_{L1}}{dt} \tag{3.41}$$

$$L_{L2}\frac{di_2}{dt} = N2\frac{d\o_{L2}}{dt} \tag{3.42}$$

When Equations 3. 36 and 3.37 are substituted in Equations 3. 28 and 3.29, the primary and secondary voltages are expressed by:

$$e_1 = R_1i_1 + L_{L1}\frac{di_1}{dt} + N1\frac{d\o_m}{dt} \tag{3.43}$$

$$e_2 = R_2i_2 + L_{L2}\frac{di_2}{dt} + N2\frac{d\o_m}{dt} \tag{3.44}$$

3.7. MATHEMATICAL MODELING OF GENERATOR

The three phase stator voltages of generator are given below:

$$e_1 = I_{a1}(jX_S + R_a) + V_1 \tag{3.45}$$

$$e_2 = I_{a2}(jX_S + R_a) + V_2 \tag{3.46}$$

$$e_3 = I_{a3}(jX_S + R_a) + V_3 \tag{3.47}$$

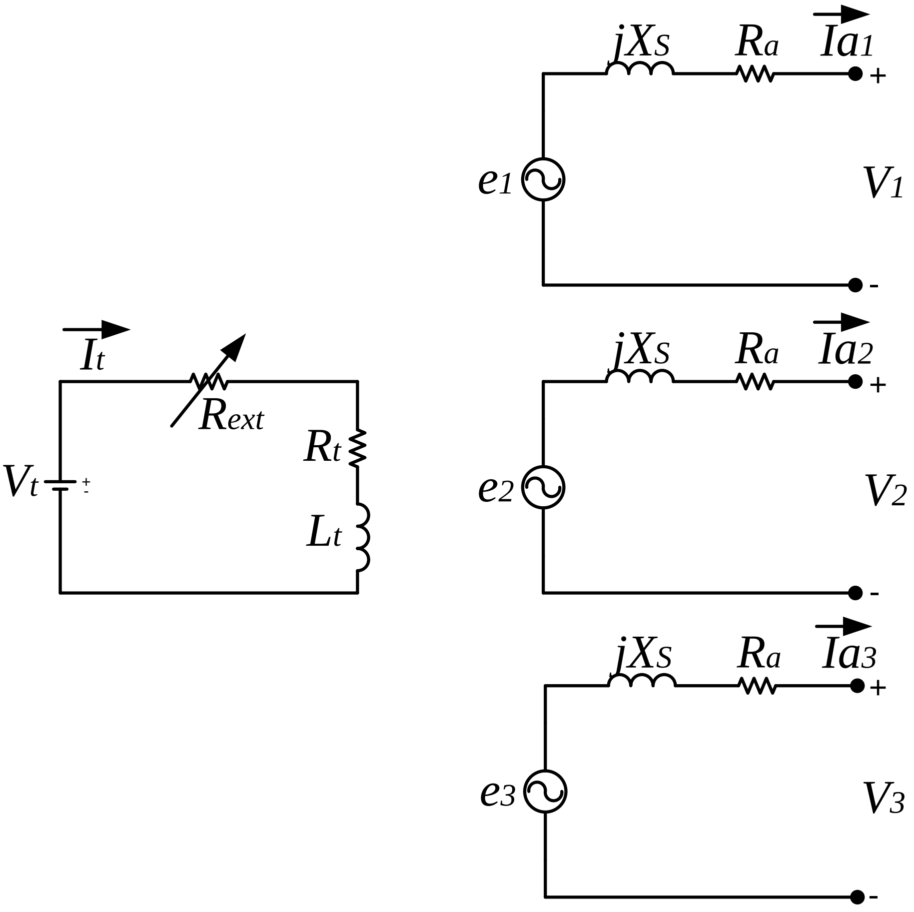

Figure 3.13. Equivalent circuit of generator [92].

PART 4

CONTROL AND OPERATION OF MICROGRID BASED ON MULTI-AGENT SYSTEM

The power system control strategies widely categorized into two characteristic types, those are centralized control and decentralized control. The principal distinction among them is in the management of functions and duties assigned to the particular controller units. Distributed generations and loads within the microgrid commonly have many differences in generation which cause high degrees of uncertainties. Furthermore, data on the amount of power and operation cost of distributed generations as well as loads are additionally not easily recognized [93]. For these reasons, relevant control strategies and management strategies are essential for the operation of microgrid effectively.

4.1. MICROGRID CONTROL STRATEGIES

4.1.1. Centralized Control

The principal concept of the centralized control system is utilizing a central control unit for gathering, merging and processing the measurement information from different apparatuses for the purpose of making control decisions. A centralized control structure commonly includes a devoted central controller which implements with a range of tasks like collecting information, executing computations and optimization and assigning control procedures for all system units. Furthermore, all these tasks are performed at one point which necessitates a large-scale communication infrastructure between microgrid central controller (MGCC) and its units to be controlled. Else disadvantage is a large reliance on MGCC which implies if there any fault happens in MGCC, the whole MG will be affected [94]. Figure 4.1 demonstrates a model of a centralized control strategy.

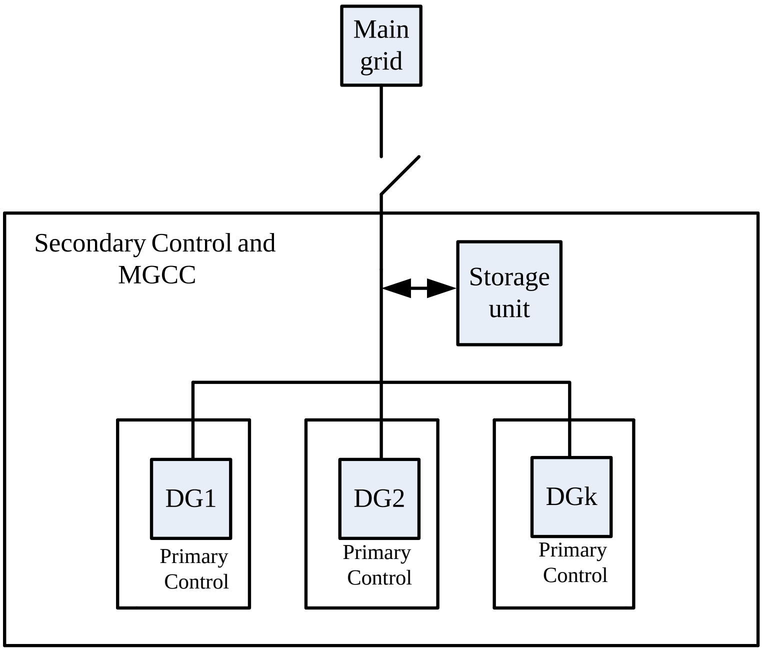

Figure 4.1. Centralized control [94].

Centralized and decentralized control are used for controlling the distributed generators outputs. The centralized control in microgrid manages the power between the different distributed generators and the main grid. All the values from the distributed generators and main grid are detected by MGCC and it offers a reference values to send to the primary control loops. MGCC recovers data from the measuring and controlling apparatuses in the microgrid and addresses these information values through the use of- decision-making units. Following the addressing of the information, MGCC will transfer control signals to the MG.

One primary merit of using the centralized control strategy is that the MG operator has a wide supervisory over the grid. This suggests the network parameters like power flow, voltage, current and frequency will be known. For this reason, the operator of the system would have an entire comprehensive viewpoint and is able to observe certain sections in the microgrid when needed. Nevertheless, one principal drawback of executing the centralized control strategy is the cost of communication network substructure. For each distributed energy resource or storing unit connected to the microgrid, an equivalent group of control gear for controlling the apparatus should also be fixed and be in synchronization with the principal MG server. This is especially unwanted when the vast majority of the distributed energy resources and apparatuses of energy storage have low capacity and therefore it could not be practicable from an economic perspective to separately govern and control every element at the microgrid level. Additionally, as a result of the necessity for addressing a significant amount of data at one central point at one time, centralized control is incapable to display the plug-and-play merit that is needed in an ever-changing MG structure. Accordingly, this restrains extension of the energy system and poses restrictions on the designing of energy systems besides other considerations [10]. Though there are drawbacks related to central control, it is, nevertheless, able to provide wider observability of microgrid activities and better understanding to make control decisions in the context of its advantages and drawbacks [34]. Overall, centralized control is greatly suitable for independent power systems that are required to sustain crucial supply and demand equilibriums in a slow altering substructure with big units of generation.

4.1.2. Decentralized Control

In decentralized control, the local controller (agents) will directly control the equipment within the microgrid based on their responsibilities and tasks. In this status, the secondary control is alongside the primary control, there is no one central processing server in order to carry out control orders for all control units in the system. In this way, the exchanging of data between the main server and clients can be reduced [95].

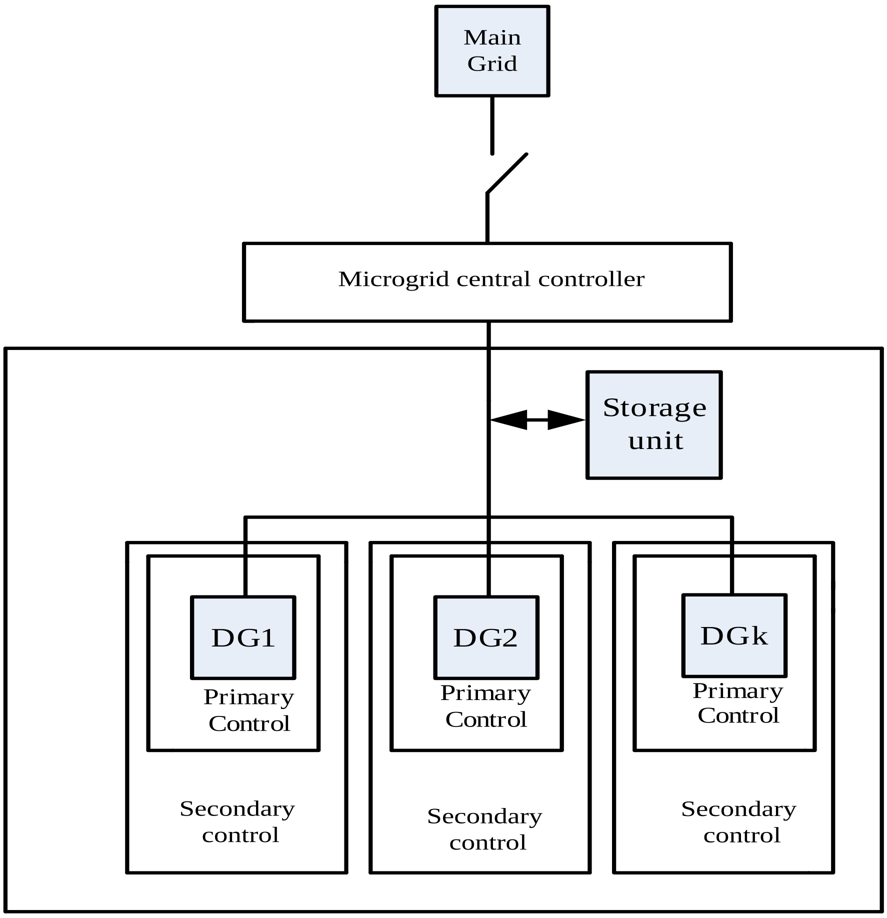

Figure 4.2. Decentralized control [94].

The technique of the decentralized control presents many essential advantages as well and they are shown in the following way:

- Expandability and openness of the system - this approach permits expanding networks of energy by means of its intrinsic plug-and-play qualities. This structure has its own flexibility. This allows distributed energy resources to be merged with the existent energy grids with lower alterations to operations of control.
- Non- intensive computing - As complicated tasks are split into small tasks assigned to several agents, there is no necessity for a central supercomputer which can minimize the implementation expenses.
- Minimum data interchange with the central server - This control strategy uses the point to point concept as local controllers are seen as points where they

collaborate with each other to achieve their duties. In this manner, it can decrease the costs of application since it does not necessitate costly central server to manage the distributed operation and storage units. Generally, decentralized control is relevant for grid-connected MGs consisting of multiple rapid changing distributed generations with diverse proprietorships.

4.2. MULTI-AGENT SYSTEM

4.2.1. Multi-Agent System Definition

Embracing MASs way to resolve optimization issues and control problems are obvious in [14, 15]. The prime goal of the MAS is to divide and distribute huge complex functions into small functions controllable ones. With regards to microgrids, information and data are decentralized which means that loss of any control element inside the MG won't menace the operation of the whole microgrid [96]. MAS is a distributed control system that consists of one or more autonomous intelligent agents with local knowledge and limited abilities. The multi-agent system is decentralized, emergent and concurrent. As far as execution costs, it is still less expensive to execute MAS distributed control due to the minimum data exchanged. This implies that the communications substructure and computer network will be lower, which will reduce execution costs. MAS is developed on the Java Agent Development Framework platform, abbreviated as (JADE). Java frame is used to create multi-agent systems in agreement with the foundation for intelligent physical agent (FIPA) features [97].

4.2.2. Agents of Autonomous

The agent can be described as a computer system that is located in a definite environment and is able of performing independent operations within this environment so as to fulfill its goal. This implies that it may take decisions for the assigned apparatus without the central controller interferes with these decisions. Regarding a microgrid with multiple DERs, it is beneficial having such a feature, therefore, there will be no delay in control actions if there is a failure of response in any of the DERs. Agents receive sensory signals from their environment, make output operations which influence it [98].

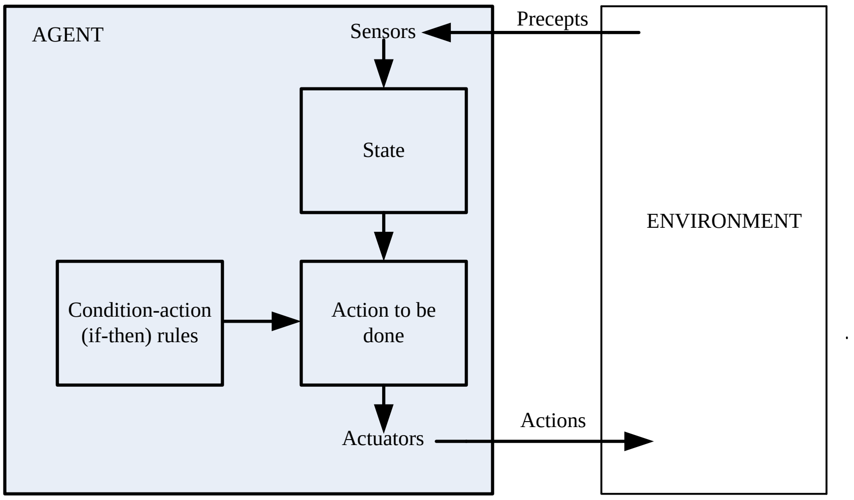

Figure 4.3. Agent environment diagram [99].

There are several characteristics for agents:

- **Social capability:** Agents can communicate and interact with each other to fulfill their targets. This is due to the fact that agents have incomplete or even no knowledge of the environment i.e. the MG in this regard. Consequently, by contacting other agents, it is capable of constantly updating itself with related information.
- **Reactivity:** Agents can respond to any alterations within the environment quickly. For instance, when any DER agent inside the MG is detached or offline, there will be a notification to other agents and consequently, they execute little changes in their algorithms to secure a smooth operation of the MG.
- **Pro-activeness:** Agents show objective-directed behaviors so as to achieve their goals. This is due to the fact that agents individually are not able to accomplish their goals except when they take the lead to communicate with other agents. For this reason, rather than being inactive, agents are deemed active units so that their objectives can be carried out.
- **Reliability**: Agents cannot give deliberately wrong or deceiving data that may probably ruin the integrity of the data interchanged.

- **Mobility:** Agents can wander from one platform to another without a lot of alterations being made to the current system. This is especially advantageous during maintenance periods. [100].

4.2.3. Foundation for Intelligent Physical Agent (FIPA) Specifications

With regard to communications between agents, the FIPA standard is utilized [101]. FIPA is a global nonprofit corporation of enterprises and organizations making agent techniques specifications. This group of criterions is formed to accomplish a high degree of interoperability within sophisticated systems. Within FIPA features, three basic roles were determined to characterize the reference module of a platform of agent. Such roles are essential for the management of the platform in addition to the description of agent management language. The 1st role necessitates Agent Management System AMS to be installed so that surveillance and control over the platform of the agent may be made. This is also needed to sustain a directory of resident agents and manage their cycle of life. The Agent Communication Channel (ACC) is the following role where it is the default prime communication technique providing trustworthy, systematic and precise message routing services. The 3rd role is necessitating a Directory Facilitator (DF) agent to be available to provide yellow page services to agents in the platform. Other FIPA features involve Agent Communication Language (ACL). This is a language utilized by agents to interchange messages. As creating of agents could be accomplished by various developers, the FIPA-ACL standard is applied thus agents running on various platforms can realize and elucidate messages. This will additionally block any vagueness and disorientation resulting from agent communications as a standard group of message format is put out in compliance with the FIPA-ACL features. Further precise data in regard to these features could be revealed in [102].

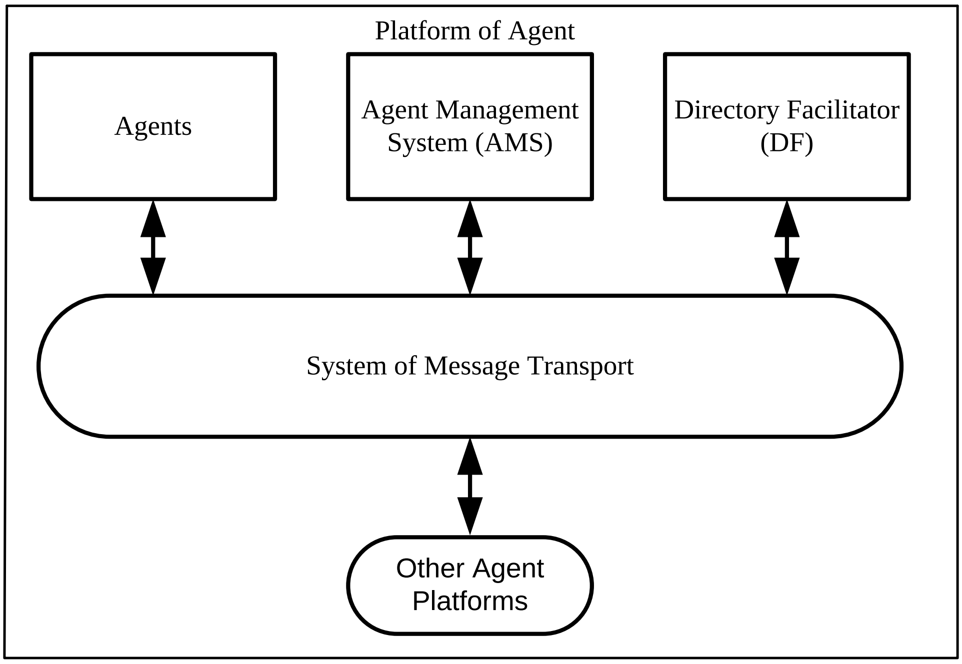

Figure 4.4. FIPA compliant agent platform [103].

4.2.4. Java Agent Development Environment (JADE)

The MAS was designed using the platform of JADE. This is a Java frame used to create MASs in agreement with the FIPA features. JADE provides an appropriate distributed platform to the designers to concentrate on agents' development to control and monitor the operation of the MG. JADE is an open source platform which can promote plug and play competencies as well and it can be scaled without greatly modifying control scheme. The agent exists inside a container and a group of containers forms a platform. Agent management service (AMS) is in charge of the management of the platform of the agents, which will maintain a directory of agent identifiers (AIDs) as well as agent situations. Every agent has to be registered in an AMS to obtain a proper agent ID. A directory facilitator (DF) offers the essential services of yellow page inside the platform, which permits the agents of discovering the other ones in the network in accordance with the services they require. Figure 4.6 shows the JADE platform [102].

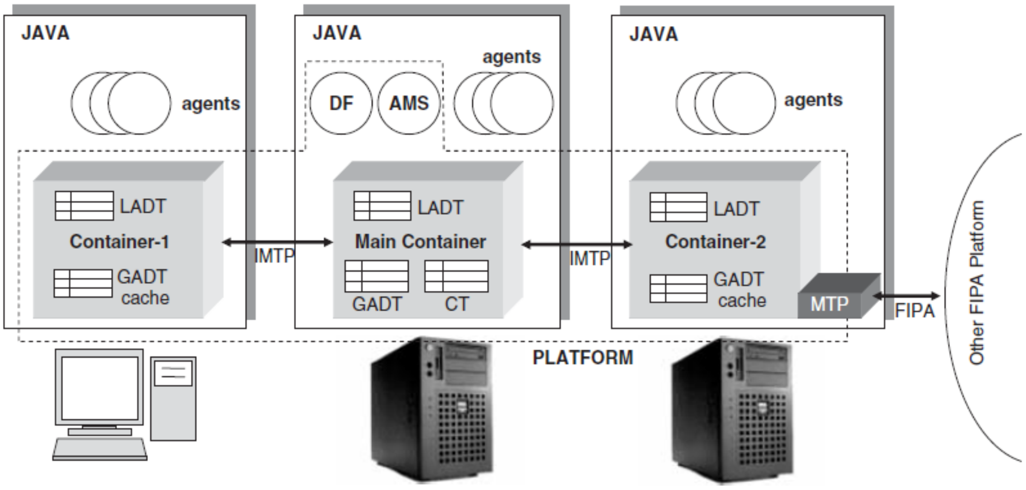

Figure 4.5. JADE platform [102].

Presently, a lot of research efforts including agent design and improvement made for multi-agent system applications. Creating a multi-agent framework from scratch could be tiresome in addition to be a waste of time. For this reason, it is crucial to check that cyberspace for a JAVA-based multi-agent framework collects all or most of the demands. A survey of many frameworks of MAS [36, 104] was made and the characterization for construction tools for three of them is briefed in Table 4.1.

Table 4.1. JADE, ZEUS and VOYAGER multi-agent system development platforms.

TOOL	JADE	VOYAGER	ZEUS
A uniform resource locator	http://jade.tilab.com/	http://www.recursionsw.com/	http://sourceforge.net/projects/zeusagent
Authorization	Open source and free	Profit product	Open source and free
Computer architecture	FIPA-compliant	Service oriented architecture	FIPA-compliant
Support of platform	Active	Portal of online	Agent communication language (ACL)
Language of programming	Java	Java	Synchronous generator
Pros	Steady platform	Hardware driver support	Scalable
Cons	Challenging for new designers	Constrained industry adoption	Weakened documentation
Developer	Research labs of telecom Italia	Recursion software Inc	British telecommunication labs

Among the accessible toolbox referenced above, JADE was chosen for this study since it complies with the core IEEE FIPA characteristics and achieves each requirements which are important in executing a standard JAVA-based multi-agent framework.

4.2.5. MACSimJX Middleware

Within MATLAB/ Simulink, the S- functions are incapable of handling many execution threads, which represents a core feature of MAS: they become not stabilized when a number of processes operate at the same time inside Simulink. For overcoming this issue, we utilize an interface MACSimJX, in order to act as a link between models of system simulated in Simulink and the MAS, turning MAS as close as possible to the practicable implementations [19]. MACSimJX contains a client-server structure, which separates the multi-agent system from MATLAB/Simulink as displayed in Figure 4.6. DERs take advantage of a distributed approach of a multi-agent system for concurrent running in order to enhance the operational proficiency of the microgrid. In Simulink, the S function permits programs scripted in other languages such as C++ and Java to operate on MATLAB [105]. For that reason, the agents are possible to be created in Java and operate on Simulink. MACSim uses the S function capability of Simulink but just as a gate to transfer data to JADE with parallel processing capability. Inside the client-server structure of MACSim, the client part is installed in Simulink through the S function and the server part is integrated in the independent program. The communication among the client and the server by using designated pipes in the windows operating system. Pipes in use are two, one of them is used to pass information of configuration while the other to pass information of simulation. This permits that the two operations run without synchronization. The MACSim server handles the correspondent operations of JADE and passes information to and from the MACSim client, which is installed in Simulink by the S function [106, 107].

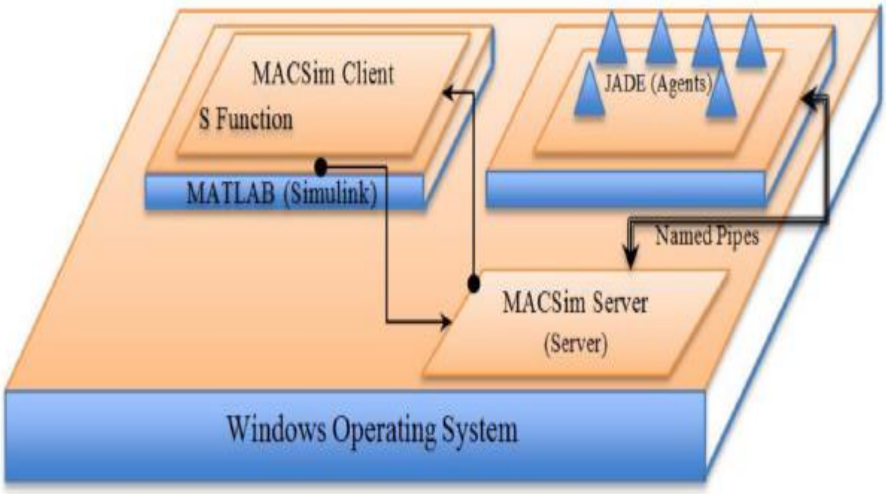

Figure 4.6. MACSimJX structure [106].

The full MACSimJX model is displayed in Figure 4.7, which demonstrates the way in which the signals are transmitted from the client part to the server part. As soon as after the arrival of simulating signals to the server part, they are conveyed to the model of agent, which is split into two parts, environment of agent and agent task force (ATF). The environment of agent offers important agent facilities like collaboration and message transfer. In this environment, there is a coordinator and agent server. The coordinator of agent sends messages to the ATF, which appoints the tasks to agents, demanding them to perform any processes essential for preparing outcomes for the determined time step. The ATF composed of all the agents. These agents work by its programmed in JAVA in the JADE environment simultaneously working on the data comes from Simulink so as to achieve the objective of optimization of power management of a microgrid [108].

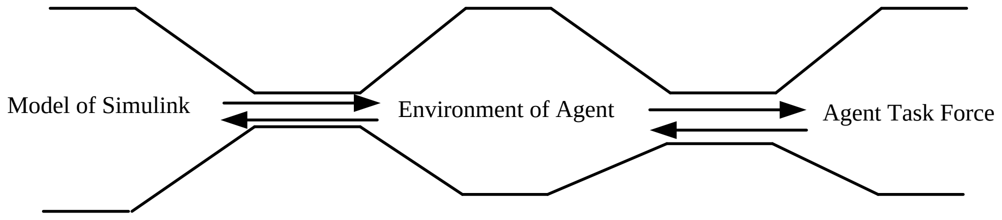

Figure 4.7. A fully model of MACSimJX [108].

4.3. APPLICATIONS OF MULTI-AGENT SYSTEM IN MICROGRID

4.3.1. Distributed Control

The current power systems in the context of microgrid have become more intricate because they contain many actuators and sensors associated with different apparatus to implement intelligent and autonomous decisions. The multi-agent system has drawn compelling attention in the current days on account of its ability to improve microgrid efficiency, decrease operation cost of generation units. A distributed control based on local agents is a promising strategy for dealing multi-agent system compared to a centralized strategy, that is costly and complex. Some of the implementations of MASs for distributed control in the microgrid are given in [22, 34, 109, 110]. Figure 4.8 shows a distributed control system for microgrid system using a MAS model. The MAS model consists of four agents distributed generation (DG) agent, control agent, user agent, and database agent.

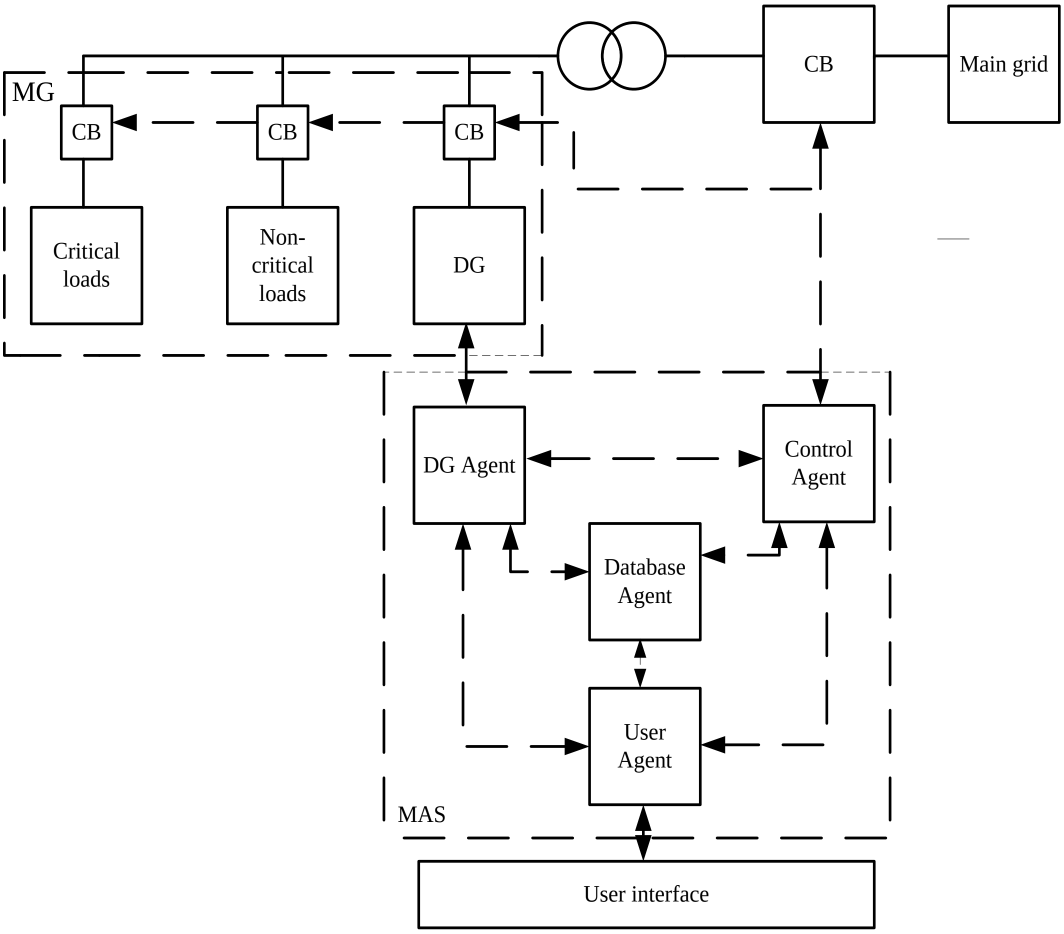

Figure 4.8. MAS architecture [22].

In this way, the MAS offers the chance to enable distributed control for the MG system. DG agent is responsible for collecting the information which are related to the distributed generations like; status of connection, availability, and energy cost. The control agent is responsible for load control and operation modes of the MG. The user agent represents the gate between the user and the system to achieve system aims. The database agent is the database for the system (agents and users) [22].

4.3.2. Protection of Microgrid

MGs comprise of a small-scale grid which links many of DERs such as PV cells, wind turbines, combined heat and power (CHP) and etc., in addition, storage apparatuses which improve the microgrid performance by reducing electricity demand during peak times, confronting network disturbances, offering power outage by standby generators and providing power for the demand in the future. The radial distribution system of power with a central power source changes to a new complex structure when DERs are added. The big capacity of the short circuit, complexity in the current path during the fault and diversity in characteristics of distributed energy resources might lead to the fact that conventional protection systems ineffective. The electrical protection must be expanded to include both microgrid operation modes. In case of a fault is detected in the main grid, the microgrid is isolated from the main grid, and must regulate its voltage and frequency, compensate the lost power for loads, especially for critical loads by DERs. In the island mode, some DERs such as micro turbines and fuel cells have a weak response to control signals. To resolve this problem, the DERs and storage units must cooperate to implement load shedding or activating storage units [37, 38, 111]. Figure 4.9 illustrated what the authors in [39] did in the side of microgrid protection.

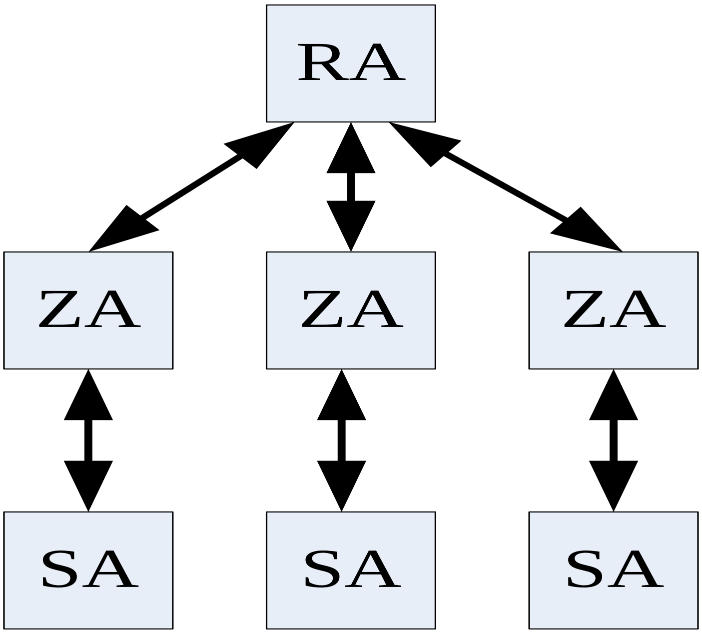

Figure 4.9. Fault detection and location by three-level MAS hierarchy [39].

They develop a MAS comprises of three layers: recloser agents layer, zonal agents layer and switch agents layer. The three layers of agents interact with each other to determine and disconnect faults in a MG based on values and direction of the current during the fault. Recloser agents observe the case of reclosers at each substation. Each zonal agent has a switch agent responsible for that zone. When a fault happens in the power system network, recloser agents send signals to zonal agents that are associated to switch agents. Each switch agent inspects its zone to isolate it in case of fault exist.

4.3.3. Service Restoration

Once locate the fault and remove it, the operation of restoring the system to its operational efficiency starts. Restoration service includes reconnecting the main grid with the microgrid as well as connecting the isolated loads from the network, in addition, disconnecting the unnecessary generators. In Ref [112-115] the researchers point out that using a MAS is more effective in detecting faults, isolating it and then restoration service than a traditional centralized system.

4.3.4. Optimization

Control of microgrid based on MASs leads to optimize the MG operation. The MAS features of power management and real-time reaction are used to prevent local power outages in microgrid systems with diverse sources and loads. These procedures must be done most competently and minimum cost as possible to become the operation of microgrid more economically applicable [22, 45, 116].

4.4. MAS BENEFITS AND DRAWBACKS

The multiple advantages of the MAS enable the incorporation of DERs to the current power system.

- Architecture Distributed: The architecture of the multi-agent system depends on local data and decision making which means it's suitable for the nature of the generation distributed.
- Flexibility: MAS allows flexibility in many respects: capacities of switch on and switch off to alter the system and non-homogenous kinds of agents controlling non-homogenous loads and sources.
- Resiliency: Multi-agent system can react rapidly and adapt to faults. Furthermore, changes in the topology of the network (disconnect/connect load

or generator) will not oppose the objectives of the local and global system (e.g. efficiency and stability).

Control of MGs using multi-agent systems has some restrictions which impede its spread widely.

- Emerging Conduct: The independent and distributed nature of agents could result in unexpected results. While agents ' goals can be programmed, it is not always possible to predetermine the impact of run-time interactions [117]. Under certain conditions (e.g. operations of the market), this kind of emerging conduct may be useful, but intrinsic uncertainness may be a disadvantage in some apps (e.g. restoration of service).
- Portability: Practical execution for MAS designs and structures can be difficult. Most of the current multi-agent system applications to control microgrid are software simulations, such as MATLAB/ Simulink, and the testing of numerous MAS approaches on real MG hardware it has not been widely tried yet.
- Scalability: The large computing power available nowadays enables designers to model larger microgrids on a single platform with many agents that coordinate the procedures on the platform. However, it is not well understood yet the capacity of MAS to scale with increased issue sizes (agents across various platforms) or variety (agents of various kinds).
- Security: The move from largely physical substructure to more intelligent technology increases the likelihood of violations of safety and privacy by malicious outer actors and disruptive components.

PART 5

VALIDATION OF OUTCOMES USING CASE STUDIES

5.1. CASE STUDY 1: FAULT DETECTED, DISTRIBUTED CONTROL, LOAD PROTECTION AND SERVICE RESTORATION

A multi-agent system is executed and merged with a microgrid simulation model. Disconnecting microgrid during fault status or power outage for securing loads (critical loads) with the available energy of DERs is the main goal of the MAS. In islanded operation mode, if the loads are greater than the capacity of DERs, then non-critical loads should be disconnected. MG is simulated using MATLAB/Simulink and then data transmitted to JADE platform to examine the operation of MAS and estimate the functioning of MAS.

Once as the simulation begins, the agents initiate communications and share information between each other and JADE exchanges information with MATLAB/Simulink through MACSimJX. Figure 5.1 demonstrates a graphical user interface (GUI) of the sniffer agent, which is a tool used to document conversations between agents. The left side displays the agents inside the container while the right side is demonstrated a graphical performance of the messages interchanged between agents, where each arrow represents a message.

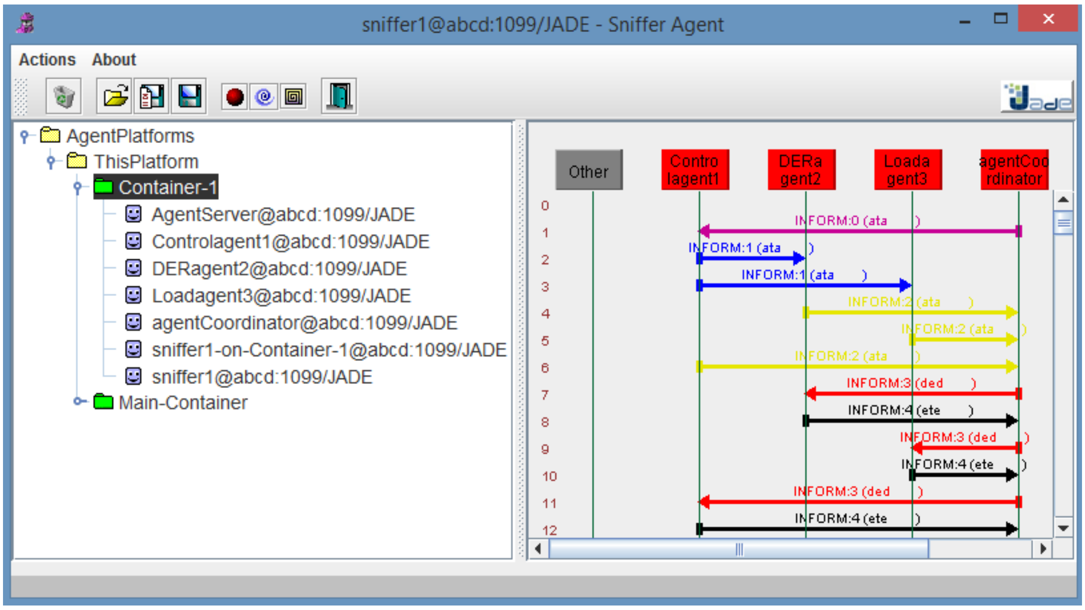

Figure 5.1. Sniffer agent GUI.

5.1.1. Fault Scenarios

The results of simulation exhibit the MAS capability of disconnecting the MG from the main grid and ensuring power flow for critical loads while faults occur in the main grid takes place. In Figure 5.2 we can see that faults at LV-network occur between 0.05-0.09 sec and 0.3-0.34 sec.

In the first 0.05 seconds, the system is in grid-connected mode. At the second 0.05, the first fault occurred. The control agent senses the alterations in the voltage of the system. It informs the agents and sends a control signal to disconnecting the MG from the main grid by opening the main circuit breaker. The fault case was revealed when the voltage level went lower than the preset limit.

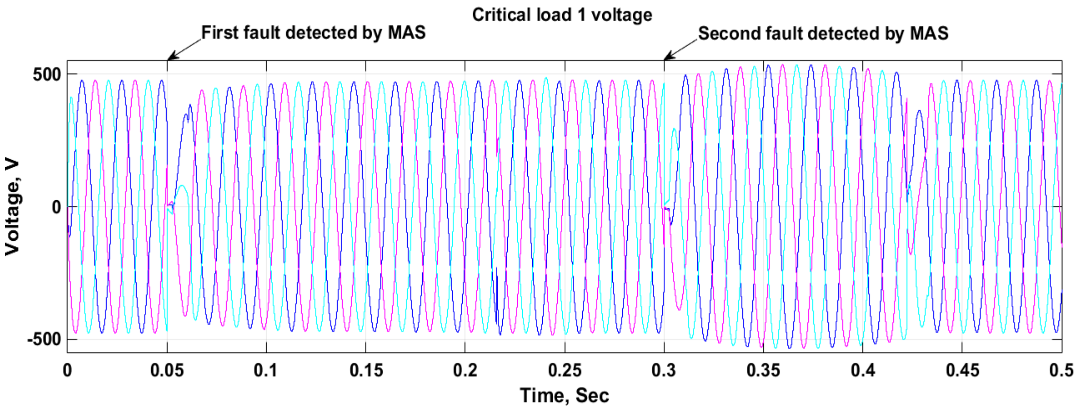

Figure 5.2. Critical load 1 voltage.

5.1.2. MAS Structure of KBU MG

In this subchapter we are designed MAS for Engineering faculty of KBU MG which consists of three agents:

- Control Agent (CA): It observes the frequency and voltage of the system in a purpose to disclose contingency conditions and takes actions to operate microgrid in island mode by opening the main circuit breaker at a common coupling point (PCC). CA sends a proposition message to distributed energy resources; it assesses the responses from DERs in accordance with the required quantity of the power and a request is sent to the optimal suggested distributed energy resource or make load shedding for non-critical loads. It furthermore makes each agent in the system aware of the operation mode of the microgrid whether it is on the connected or islanded mode.
- DER Agent: This one gathers the data associated with the DERs, additionally, it observes and controls levels of the distributed energy resource power. Based on the received message from the control agent it sends a control signal for connecting or disconnecting the respective circuit breaker.
- Load Agent (LA): This agent contains data of loads like consuming power and loads number. The load agent also contains critical and non-critical load priority. It deals with the load shedding message by isolating the respective load.

Figure 5.3 shows the block diagram of Engineering faculty MG and proposed MAS.

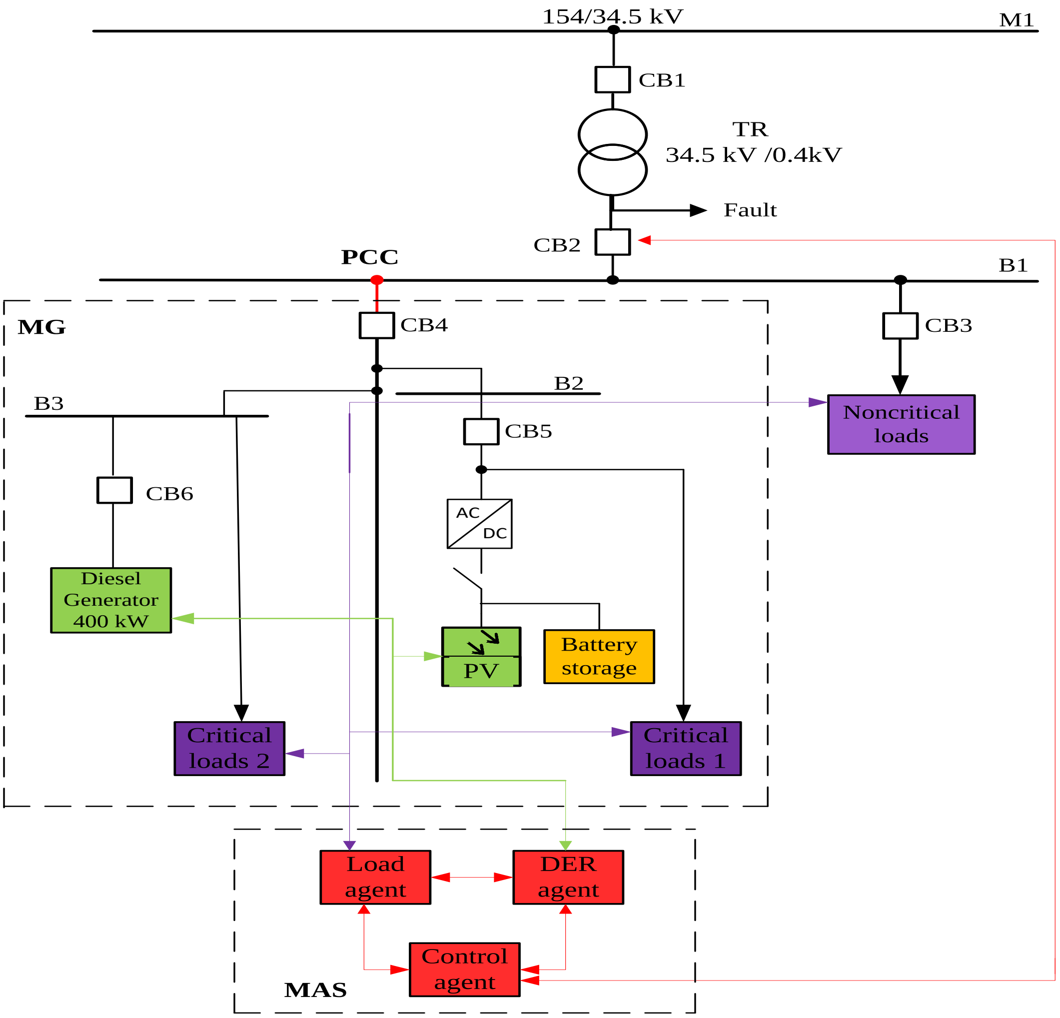

Figure 5.3. Engineering faculty of KBU MG and MAS control.

In Table 5.1 are given technical characteristics of KBU MG components.

Table 5.1. Characteristics of KBU MG component.

COMPONENT	UNITS NUMBER	MIN.POWER. kW	MAX.POWER. kW
Generator	1	375	400
PV	4	21	24
Critical load1	3	17	20
Critical load2	20	190	195
Non-critical load	35	530	550

The flow chart in Figure 5.4 illustrates the behavior of control agent.

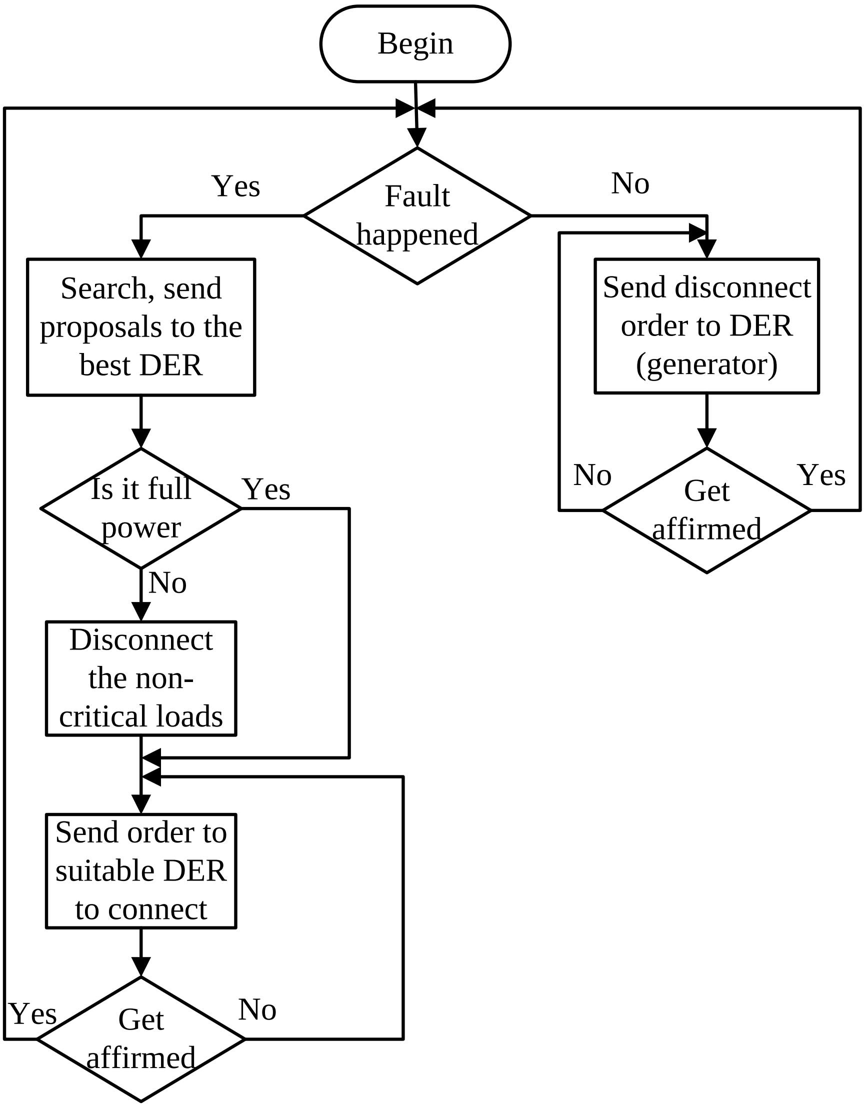

Figure 5.4. Behavior of control agent.

5.1.3. Microgrid Simulation Circuit Description

To implement the suggested MAS, a testbed is simulated in MATLAB/Simulink in form of a distribution network comprised of two DERs (PV panels and emergency generator), grid interface for connecting the PV panels to the network (MPPT controller, boost converter and inverter), three loads (critical load 1, critical load 2 and non-critical load) these loads have been connected to circuit breakers to control it, these are illustrated in Appendix A.3.

5.1.4. Simulation Results and Discussion

There are four scenarios can be discussed:

5.1.4.1. Grid-Connected Mode (GCM)

Both frequency and voltage of MG are controlled to follow the required values of the frequency and voltage of the grid. The total loads of the MG are 762 kW divided into 17 kW critical loads1, 195 kW critical loads 2 and 550 kW non-critical loads as demonstrated in Figures 5.5, 5.6 and 5.7, respectively. At the time when the grid-connected mode from t=0 sec to t=0.05 sec, the PV panels supply 24 kW, the main grid supplies 800 kW and the generator is in turn off. The entire power needed for both critical and non-critical loads is provided by PV panels and the main grid.

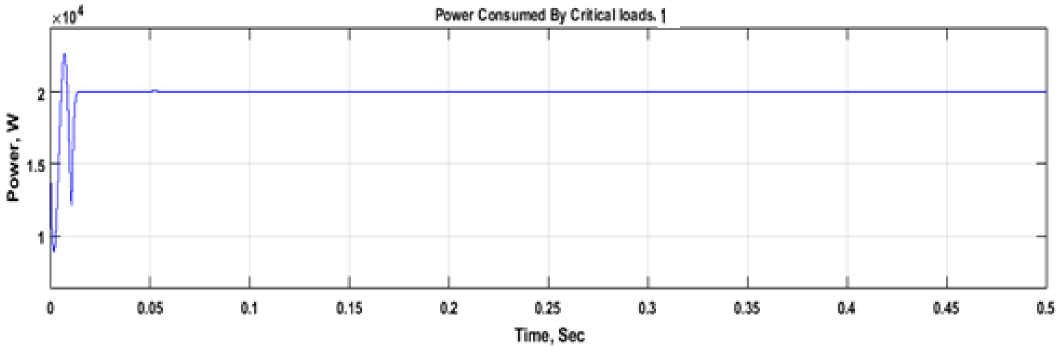

Figure 5.5. Power of critical load 1.

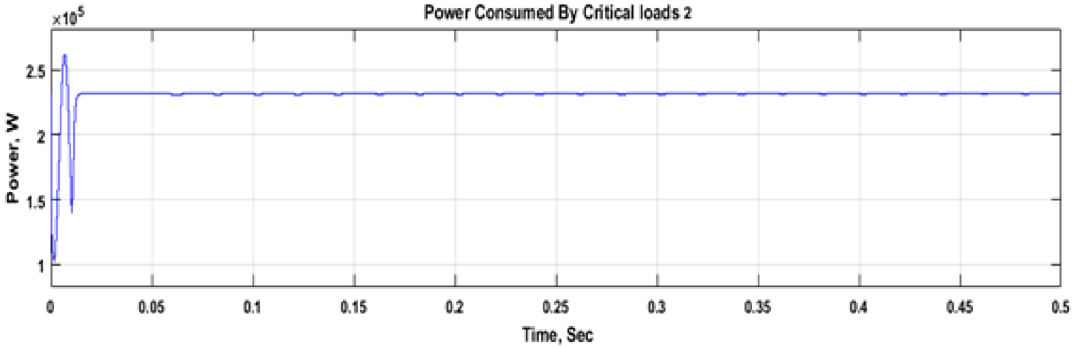

Figure 5.6. Power of critical load 2.

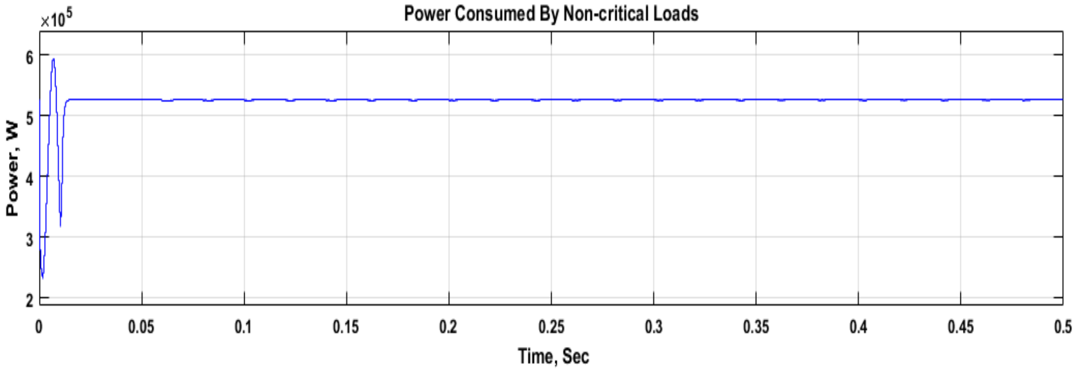

Figure 5.7. Power of non-critical load.

5.1.4.2. Transition Period (TP)

As soon as the control agent senses the fault at t=0.05 sec, it notifies the DER and load agents. The control agent transmits control signal to the main CB to disconnect the main grid as shown in Figure 5.8.

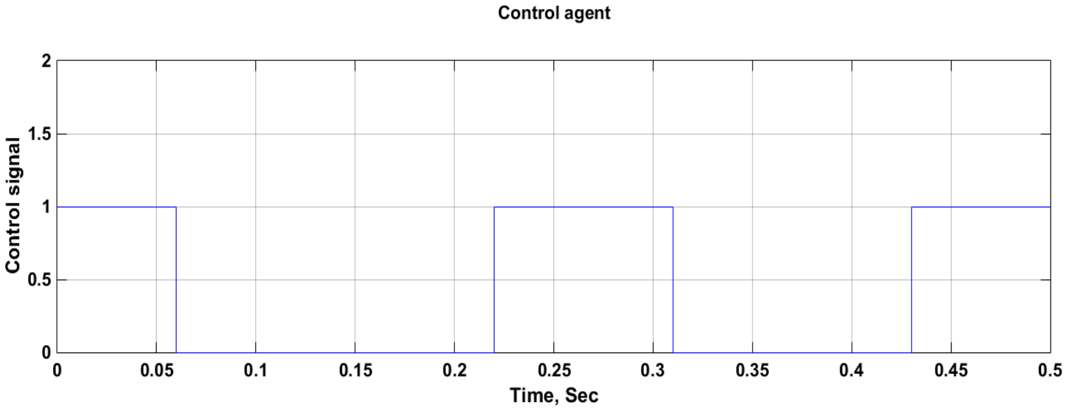

Figure 5.8. Control signals of control agent.

It executes one more task by demand the power production and consumption from DER and load agent. In this study, the distributed energy resource agent connects the generator of 400 kW to secure the critical loads as shown in Figure 5.9.

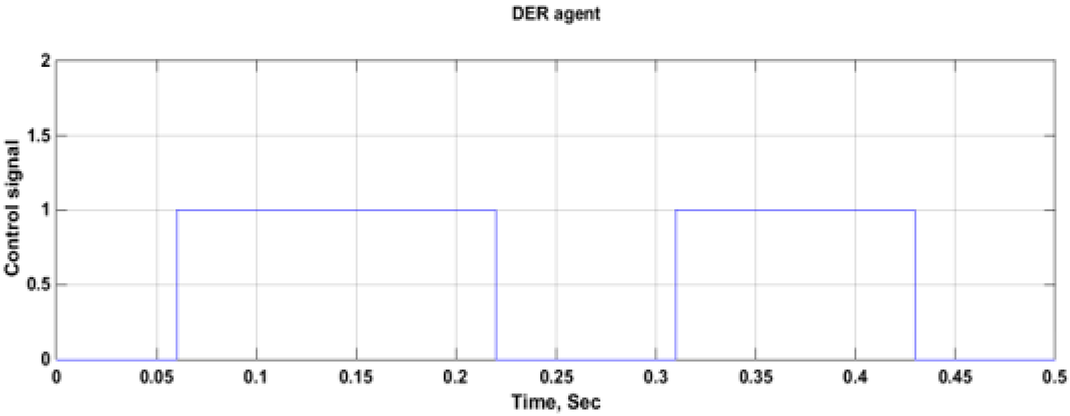

Figure 5.9. Control signals of DER agent.

Figure 5.10 shows the transition period (TP).

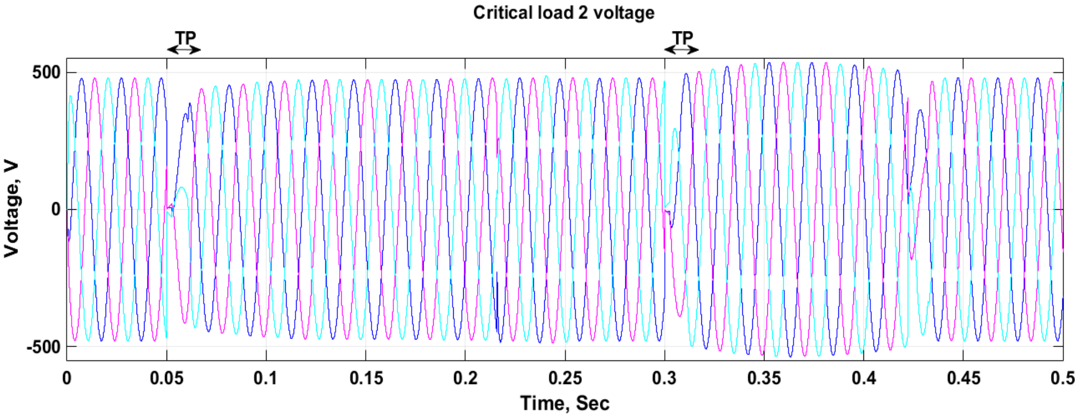

Figure 5.10. Critical load 2 voltage.

5.1.4.3. Islanded Mode (IM)

After the fault happened at 0.05 sec, the MG is isolated and the operation mode of the MG transforms to island mode, the critical loads are fully provided from distributed energy resources (PV panels and generator). The total load of the system is of 762 kW and the distributed energy resources (PV and generator) produce 424 kW to feed these critical loads. The rest of the non-critical loads (550 kW) will be thrown out by the load agent for conserving the stabilization of the system as demonstrated in Figure 5.11.

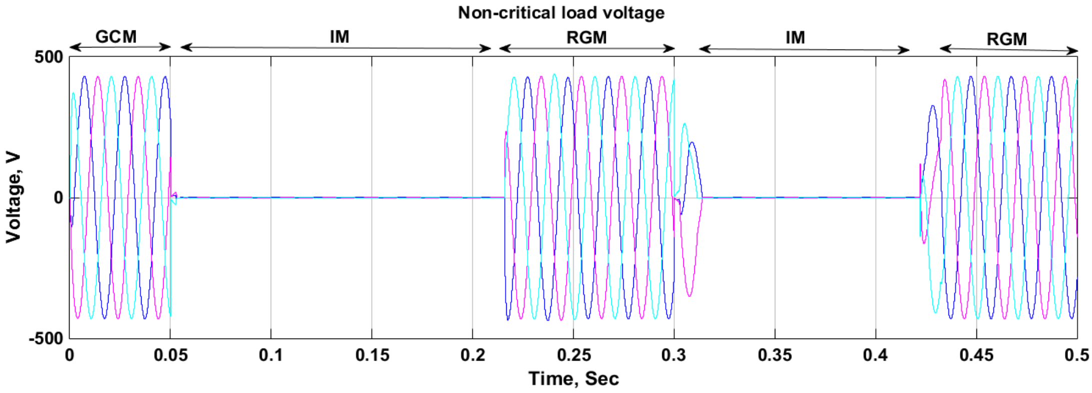

Figure 5.11. Non-critical load voltage.

5.1.4.4. Restoring to The Mode of Grid-Connected (RGM)

As soon as the main grid voltage attains to the allowable value, the control agent senses it and it notifies to the distributed energy resource agent and load agent. The control agent transmits the signal of control (closes) to the main CB to transform from islanded operation mode to grid-connected operation mode. The DER agent sends the signal of control (opens) to disconnect the generator after coordination with the control agent. The load agent examines whether a sufficient power is available and reconnects the non-critical loads as illustrated in Figure 5.11 in the intervals between t=0.23 sec to t=0.3 sec and from t=0.43 sec to t=0.5 sec.

5.2. CASE STUDY 2: OPTIMIZATION OF MICROGRID

The goal of optimization is to demonstrate that the MG can be efficaciously controlled in a distributed way with increasing economic advantages at the same time. In this thesis, a MAS has been suggested to manage and make a power balance between load demand and generated power with maximum efficiency and reduce fuel cost for a microgrid.

5.2.1. Suggested Approach

The primary precept of the suggested approach is to design a representative agent for each component of the microgrid. The suggested methodology of this study is depended on the ability of information interchange among agents and their associated elements in the microgrid. This interchange of information is bi-directional, the first direction to regain measures (power, voltage, current, etc.) and the second direction works upon the physical part of the microgrid, so as to execute various tasks as circuit breakers ON/OFF or changes the operation modes from grid-connected mode to island mode or vice versa. So, the multi-agent system submits the intelligent interface of the microgrid, when each agent is installed in a system set up with its associated element in the microgrid.

As portrayed in Figure 5.12 our microgrid model comprises of two distributed energy resources (PV panels and generator) and three loads. The elements of the microgrid are represented by local agents: power generation agent for distributed energy resources, load agent for loads, control agent to control point common coupling (PCC) and monitoring agent for the microgrid.

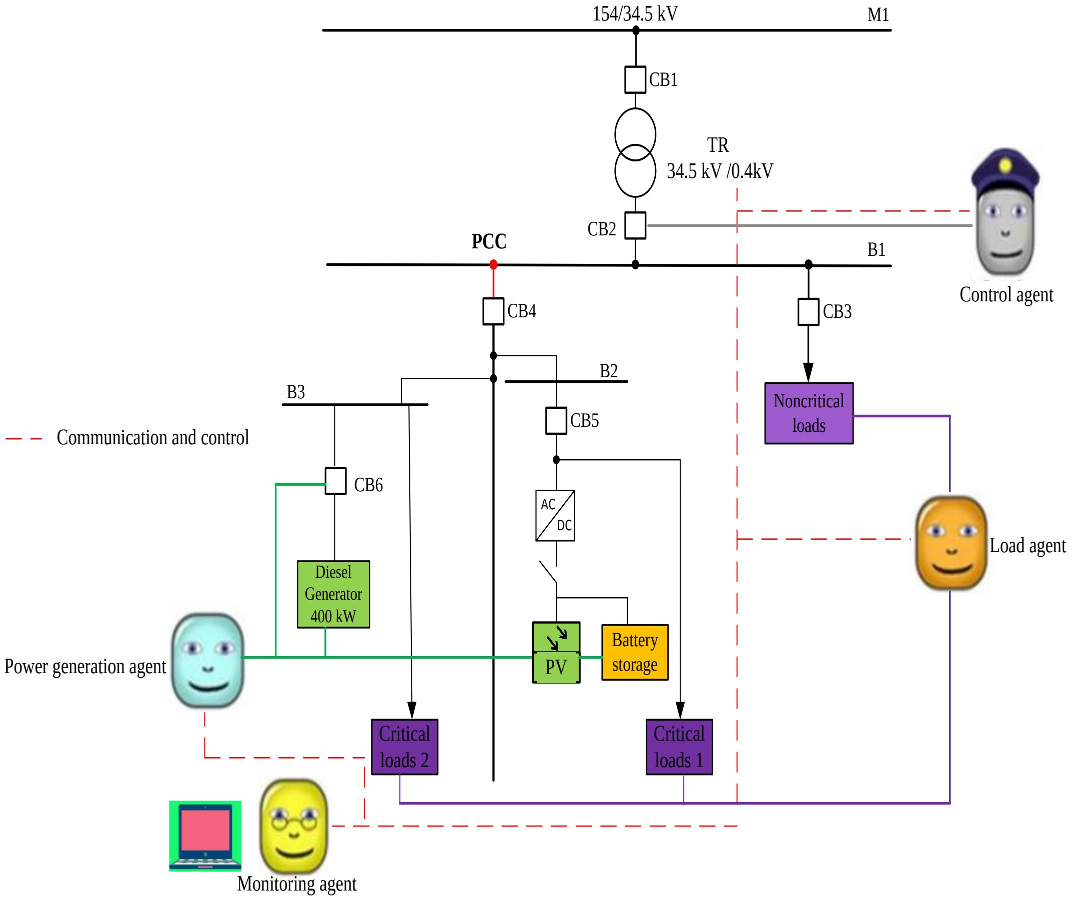

Figure 5.12. MAS architecture.

The precept of the suggested management approach depends on information exchanged by messages between agents to make appropriate decisions. The suggested algorithm for the management of operation is exhibited in Figure 5.13. It is imperative to take note of that the drawn graph shows both the program of management and the cooperation among agents.

Where: Pd is demand for power, Ppv is the produced power from PV panels and Pgen is the produced power from the generator. The multi-agent system should be capable to manage events, for example, the demand for power. For this event, and as we know the operation modes of the MG are grid/island modes. In this study, two cases are possible for island mode:

- If the amount of produced power from the PV panels is greater than or equal to the demand for power Pd, loads are fed according to messages exchanged among the power generation agent and load agent.
- If the produced power from PV panels not sufficient to feed loads the power generation agent transmits power request to the generator to be compensated for power shortages.

If the amount of power from PV panels and generator is not enough to feed all loads, the management of this case relies upon the operation mode of the MG. The control agent connects the main grid to the MG and starts a power purchase stage. The multi-agent system takes decisions dependent on an optimization algorithm which determines the minimal cost of power.

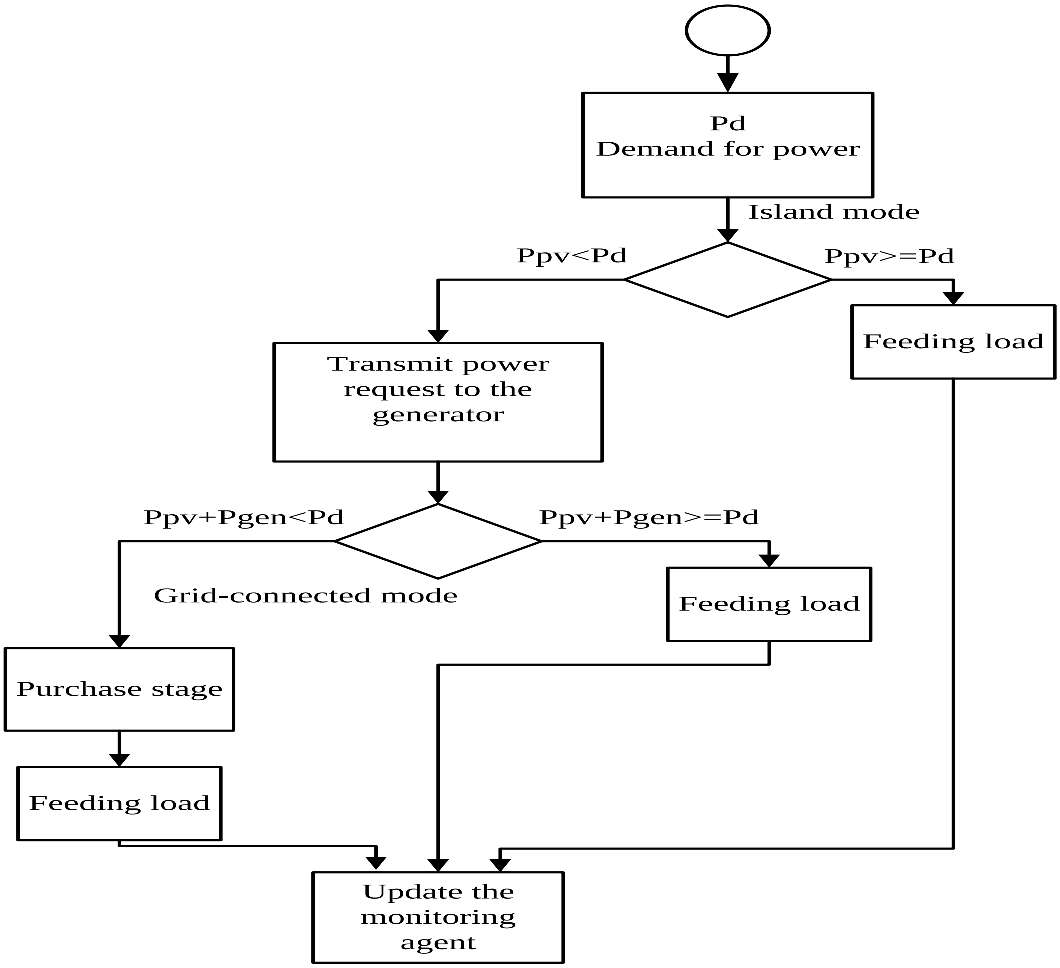

Figure 5.13. Operation of microgrid depending on the suggested management algorithm.

5.2.2. Implementation of Agents

This part offers the functions and responsibilities of agents which have been used and developed in JADE environment:

- Load agent: It is responsible for specifying the amount of load demand or power which is received from the microgrid and main grid, also it informs power generation agent and control agent by details.
- Power generation agent: It is used to control the power generation from the PV panels, generator and main grid based on settings of the load demand or load power from the load agent.
- Control agent: It controls the operation modes of the MG (grid-connected mode and island mode) depended on the details which are received from power generation and load agents.
- Monitoring agent: The monitoring agent is used to display the actual load power, power generation, system efficiency and operation modes of the system according to information from the load agent, power generation agent and control agent.

5.2.3. Simulation Results and Analysis

A multi-agent system was executed on the JADE platform and merged with the microgrid simulation model on the MATLAB/Simulink also, the accompanying simulation outcomes are discussed and analyzed. Make a power balance between load demand and power generation with maximum efficiency and reduce cost is the main goal of the multi-agent system. Two load profile settings (is how much amount of maximum load connected to the system) with fourteen cases have been used for the purpose of testing the proposed approach.

Based on load profile settings the amount of power that generation units will supply to the loads is the main task of the MAS.

5.2.3.1. Agent Operation

Once as the simulation begins, the agents initiate to perform their tasks. The agents initiate communications and share information between each other and JADE exchanges information with MATLAB/Simulink through MACSimJX. Figure 5.14 demonstrates a graphical user interface (GUI) of the sniffer agent.

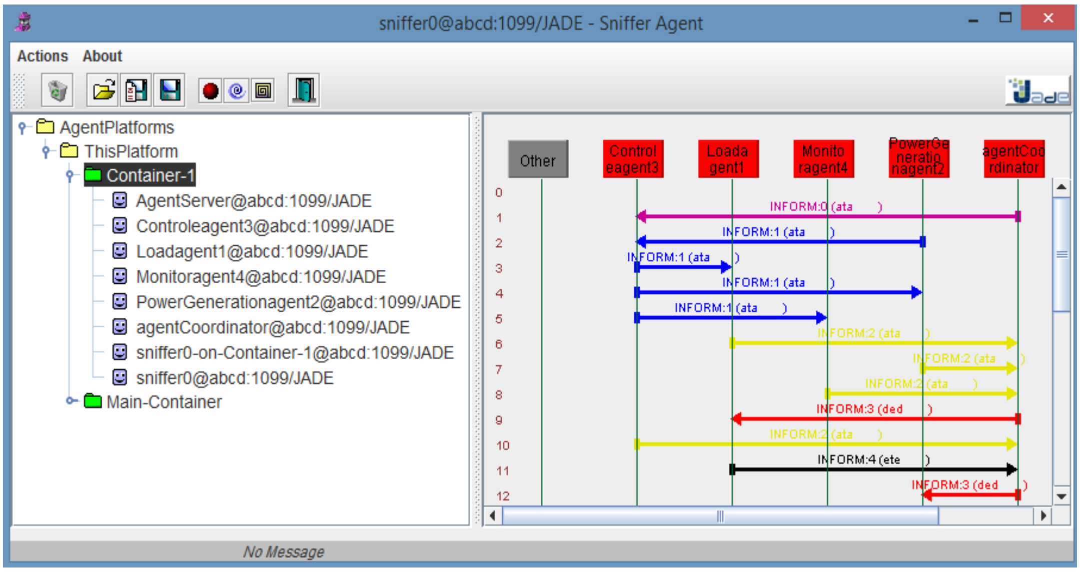

Figure 5.14. Communication and interaction among agents.

The outcomes of performance of the proposed multi-agent system (agents) for each load profile setting have been displayed in three case studies as shown:

Load Profile Setting 1:

It contains three case studies

Case Study A (Performance of the Suggested MAS)

The following figures illustrate the performance of the suggested MAS. Figure 5.15 shows load profile setting 1 of the system according to Table 5.2. Load profile setting is how much maximum load power connected to the system at different times. Based on load profile setting the required power is determined from generation units.

Table 5.2. Load profile setting 1.

TIME (sec)	LOAD1 (kW)	LOAD2 (kW)	LOAD3 (kW)	TOTAL (kW)
0-0.1	17	0	0	17
0.1-0.2	0	195	0	195
0.2-0.3	17	195	0	212
0.3-0.4	0	0	550	550
0.4-0.5	17	0	550	567
0.5-0.6	0	195	550	745
0.6-0.7	17	195	550	762

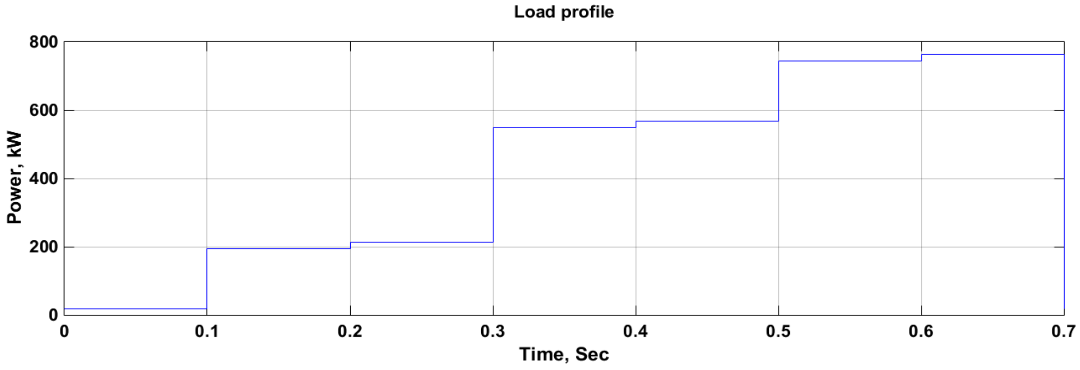

Figure 5.15. Load profile setting 1 of the system.

Figure 5.16 shows the actual load power of the system.

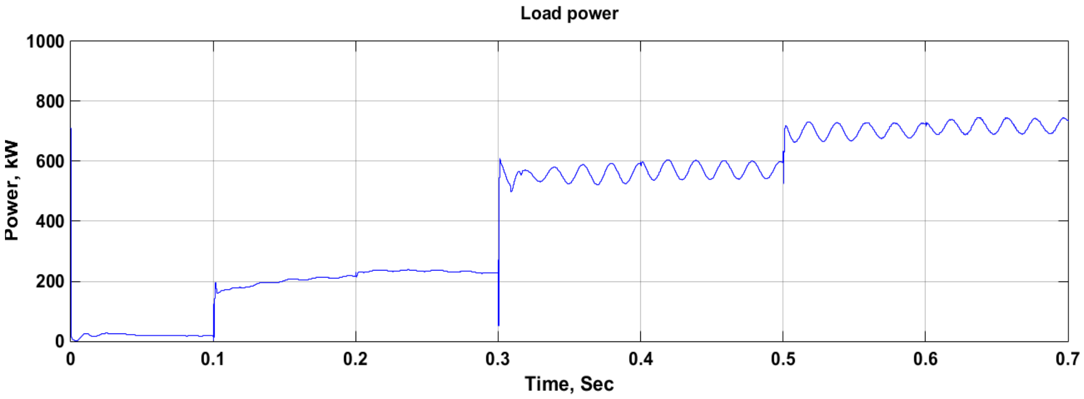

Figure 5.16. Load power of the system.

Figure 5.17 shows the power generation of the system. Power generation agent controls the generated power from generation units to get maximum efficiency based on the details which are received from load agent.

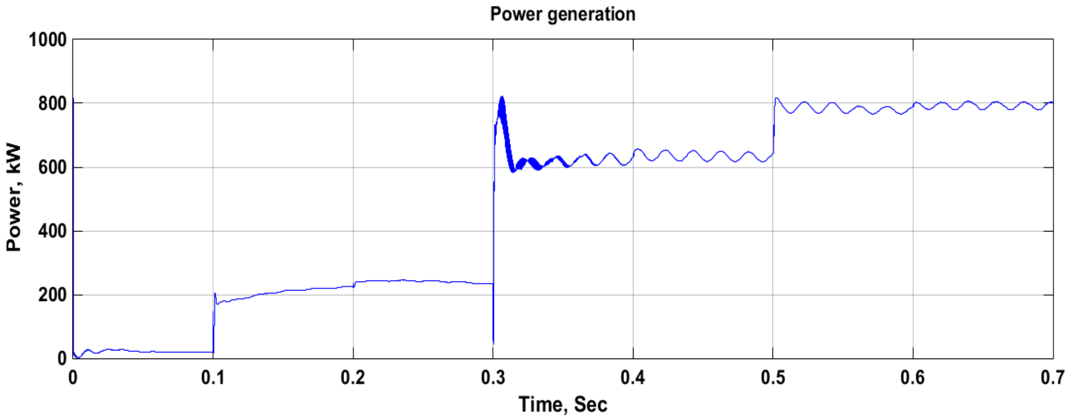

Figure 5.17. Power generation of the system.

Figure 5.18 shows the balance the power of the system (total generation – actual load power). In other words, is how much power which will save after power supplied the loads.

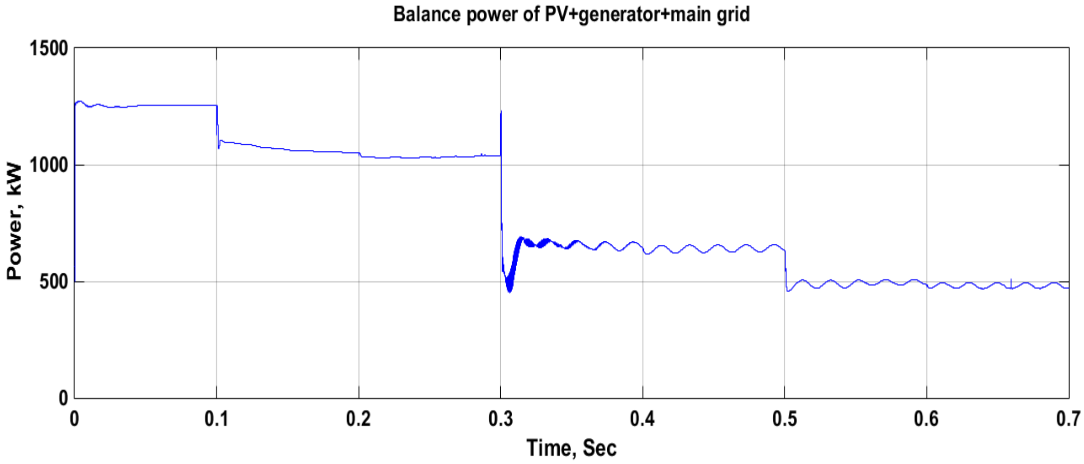

Figure 5.18. Balance power of system “PV panels – generator – main grid”.

Figure 5.19 shows the efficiency of the system. System efficiency equal to ratio of actual load power to power generation. It ranges from 90.7% to 96.6% these values reflect the ability of proposed MAS to make a power balance between demand for power and generated power.

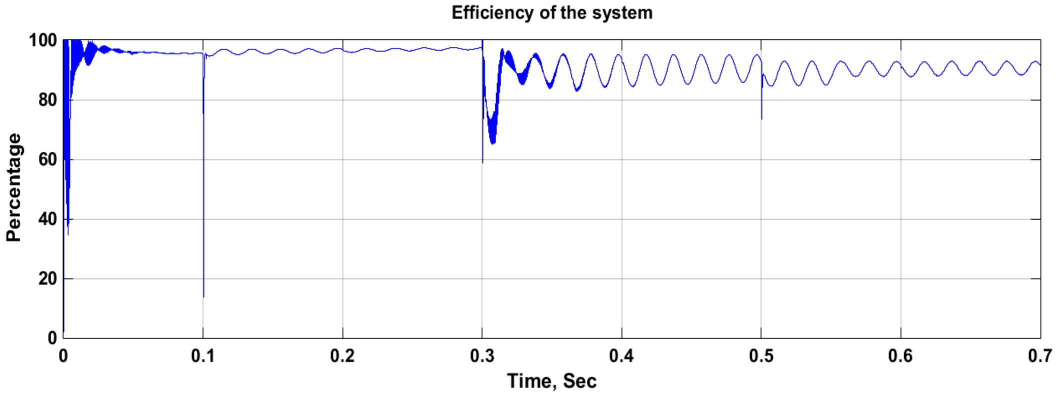

Figure 5.19. Efficiency of the system.

Case Study B (Control Signals of the Suggested MAS).

This case study contains control signals of PV, generator and main grid. Figure 5.20 shows the PV ON/OFF statuses. In the period from 0-0.1 sec all loads are fully supplied from PV panels.

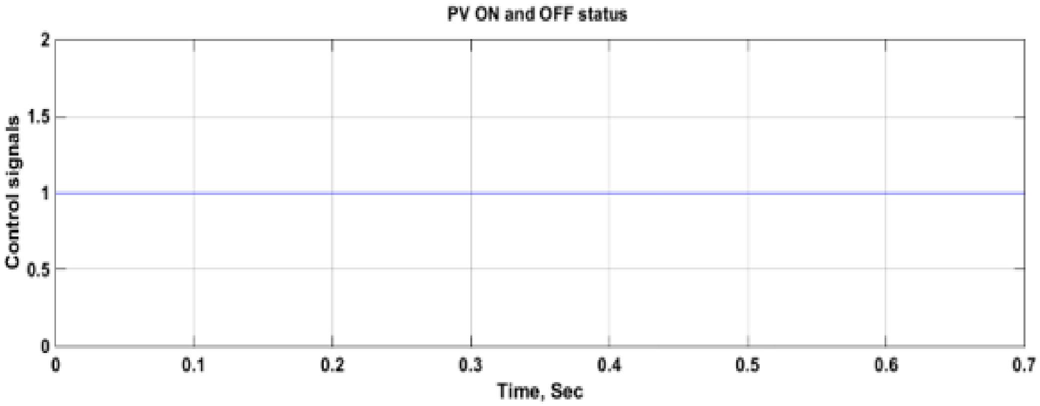

Figure 5.20. Control signals of PV panels.

Figure 5.21 shows the generator ON/OFF statuses. The generator is turn-on just in the period from 0.1-0.3 sec.

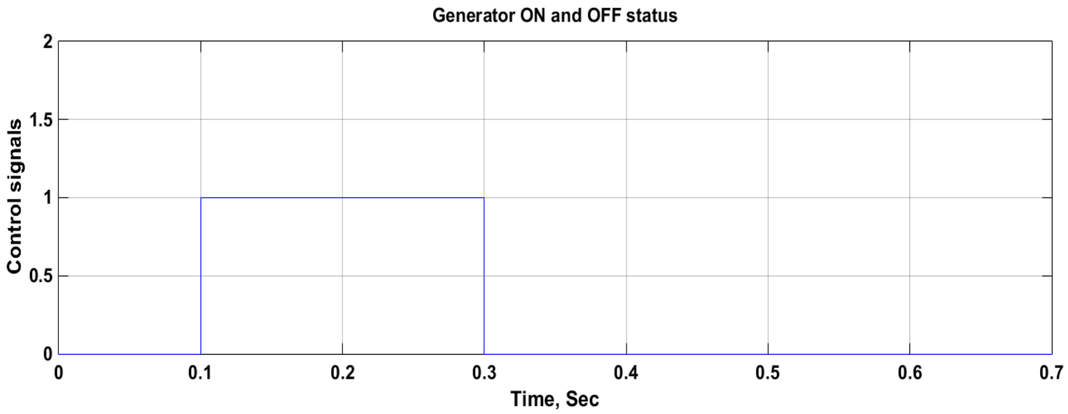

Figure 5.21. Control signals of the generator.

Figure 5.22 shows the main grid ON/OFF statuses. The system is in the grid-connected mode in the period from 0.3-0.7 sec.

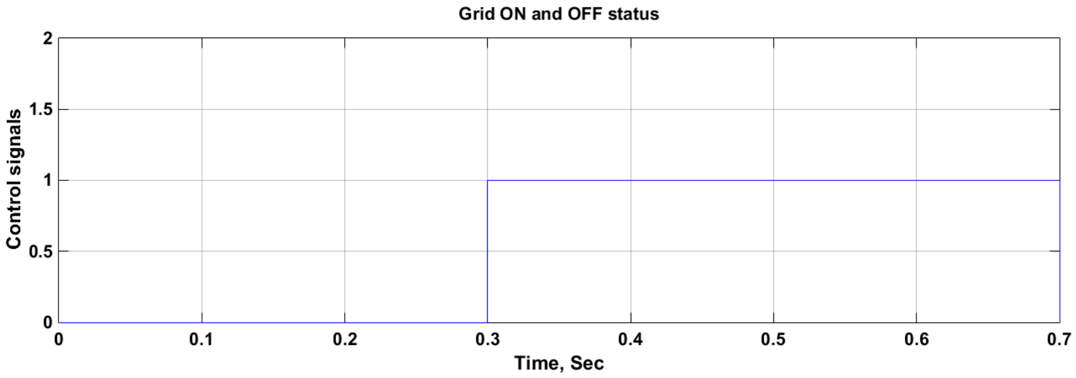

Figure 5.22. Control signals of the main grid.

Table 5.4 shows operation modes of microgrid concluded for case studies A and B.

Table 5.3. Operation modes of the microgrid during different loads.

TIME (sec.)	0-0.1	0.1-0.2	0.2-0.3	0.3-0.4	0.4-0.5	0.5-0.6	0.6-0.7
LOAD (kW)	17	195	212	550	567	745	762
OPERATION MODES	Island mode	Island mode	Island mode	Grid mode	Grid mode	Grid mode	Grid mode

Time 0-0.1 sec:

During this time load profile setting is 17 kW, actual load power is around 20 kW, power generation is around 20.9 kW, the efficiency of the system is 95.6 % and the connection is in an island mode. The control signal for PV panels is one and control signals for generator and the main grid are zero. The total load is 17 kW and the PV panels can supply up to 24 kW and no need to purchase power from the main grid that’s why the system is in an island mode.

Time 0.1-0.2 sec:

During this time load profile setting is 195 kW, actual load power is around 210 kW, power generation is around 220 kW, the efficiency of the system is 95.4 % and the connection is in an island mode. The control signals for generator and PV panels are one and the control signal for the CB of the main grid is zero. The total load is 195 kW, the PV panels and the generator can supply up to 424 kW and no need for purchasing electrical power from the main grid.

Time 0.2-0.3 sec:

During this time load profile setting is 212 kW, actual load power is around 225 kW, power generation is around 234 kW, the efficiency of the system is 96.1% and the connection is in an island mode. The control signals for generator and PV panels are one and the control signal for the CB of the main grid is zero. The total load is 212 kW, the PV panels and the generator can supply up to 424 kW and no need for buying electrical power from the main grid.

Time 0.3-0.4 sec:

During this time load profile setting is 550 kW, actual load power is around 588 kW, power generation is around 628 kW, the efficiency of the system is 93.6 % and the connection is in a grid-connected mode. The control signals for PV panels and the main grid circuit breaker are one and the control signal for the circuit breaker of the generator is zero. The total load is 550 kW, the PV panels and generator can supply up to 424 kW but the current load is 550 kW so the PV panels and the main grid will supply the power to the load and the generator is in shut off condition.

Time 0.4-0.5 sec:

During this time load profile setting is 567 kW, actual load power is around 590 kW, power generation is around 650 kW, the efficiency of the system is 90.7 % and the connection is in a grid-connected mode. The control signals for the PV panels and main grid are one and the control signal for the circuit breaker of the generator is zero. The total load is 567 kW, the PV panels and the generator can supply up to 424 kW but the current load is 567 kW so the PV panels and the main grid will supply the power to the load and the generator is in shut off condition.

Time 0.5-0.6 sec:

During this time load profile setting is 745 kW, actual load power is around 730 kW, power generation is around 787 kW, the efficiency of the system is 92.7 % and the connection is in a grid-connected mode. The control signals for PV panels and main grid are one and the control signal for the circuit breaker of the generator is zero. The total load is 745 kW, the PV panels and the generator can supply up to 424 kW but the current load is 745 kW so the PV panels and the main grid will supply the power to the load and the generator is in shut off condition.

Time 0.6-0.7 sec:

During this time load profile setting is 762 kW, actual load power is around 745 kW, power generation is around 803 kW, the efficiency of the system is 92.7% and the connection is in a grid-connected mode. The control signals for PV panels and the main grid are one and the control signal for the generator is zero. The total load is 767 kW, the PV panels and the generator can supply up to 424 kW but the current load is

762 kW so the PV panels and the main grid will supply the power to the load and the generator is in shut off condition.

Case Study C (Loads Windows)

Load 1 Window:

It contains the instantaneous voltage across load 1, the instantaneous current through load 1 and the actual power for load 1. Figure 5.23 a illustrates load 1 voltage. It is controlled to follow the required value of the grid voltage.

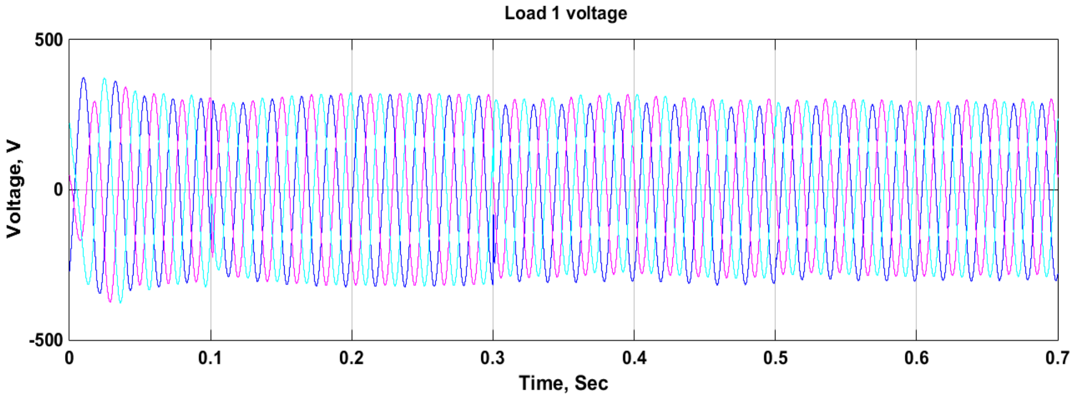

Figure 5.23 a. The instantaneous voltage across load 1.

Figure 5.23 b illustrates load 1 current.

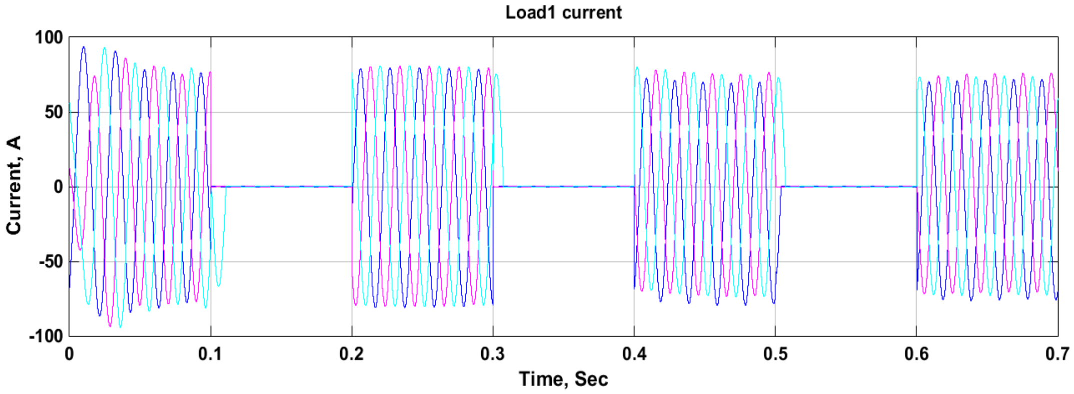

Figure 5.23 b. The instantaneous current across load 1.

Figure 5.23 c illustrates load 1 power. Load 1 is linked to the system during these periods 0-0.1 sec, 0.2-0.3 sec, 0.4-0.5 sec and 0.6-0.7 sec as per load profile setting 1, as mentioned in Table 5.1.

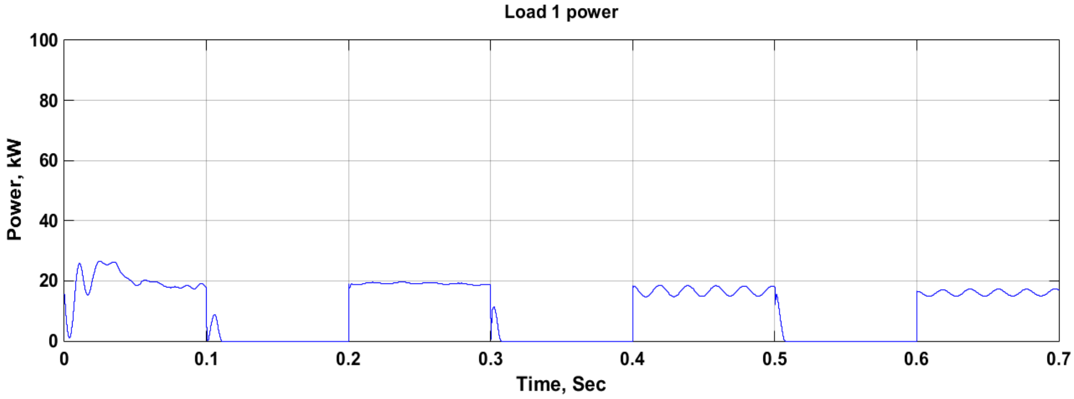

Figure 5.23 c. The actual power for load 1.

Load 2 Window:

It contains the instantaneous voltage across load 2, the instantaneous current through load 2 and the actual power for load 2. Figure 5.24 a illustrates load 2 voltage.

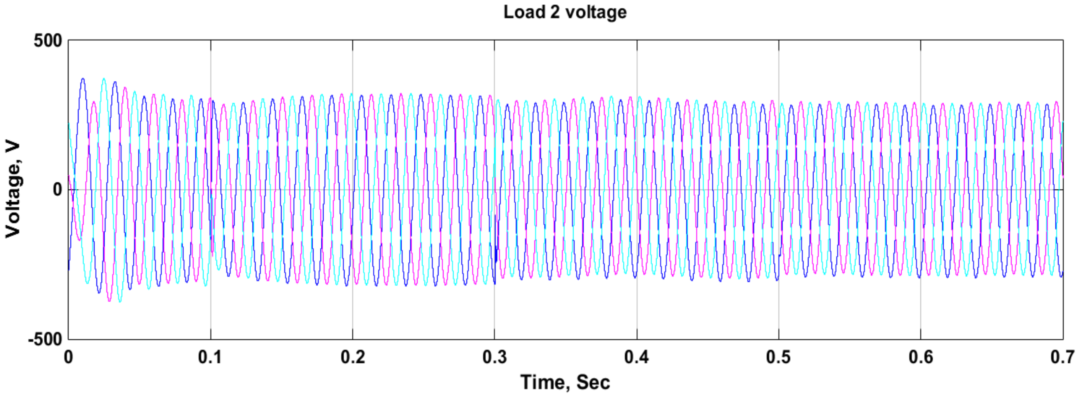

Figure 5.24 a. The instantaneous voltage across load 2.

Figure 5.24 b illustrates load 2 current.

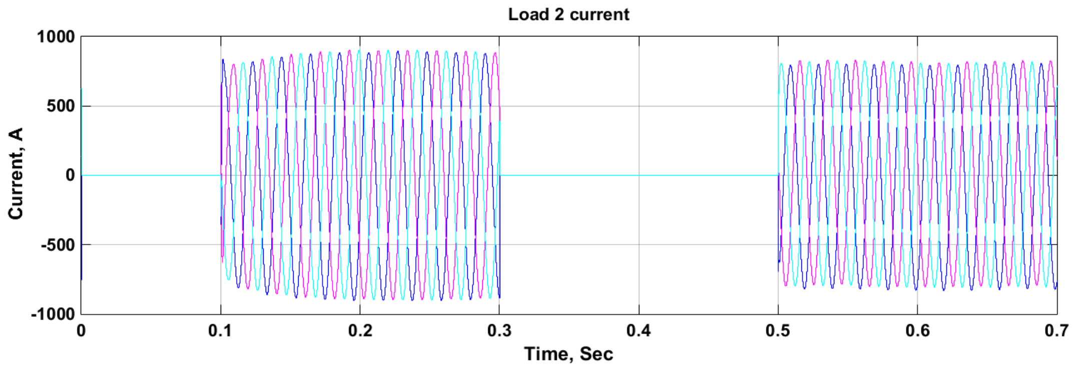

Figure 5.24 b. The instantaneous current across load 2.

Figure 5.24 c illustrates load 2 power. Load 2 is connected to the system during these periods 0.1-0.3 sec and 0.5-0.7 sec as per load profile setting 1 (see Table 5.1).

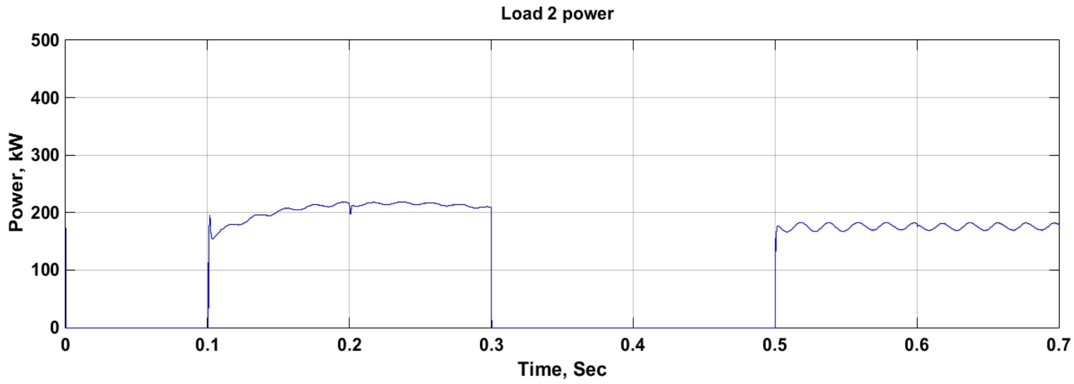

Figure 5.24 c. The actual power for load 2.

Load 3 Window:

It contains the instantaneous voltage across load 3, the instantaneous current through load 3 and the actual power for load 3. Figure 5.25 a illustrates load 3 voltage.

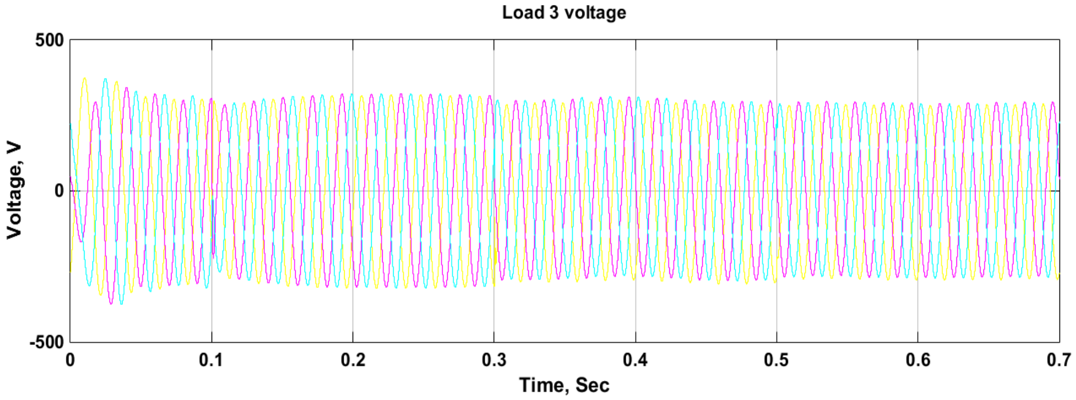

Figure 5.25 a. The instantaneous voltage across load 3.

Figure 5.25 b illustrates load 3 current.

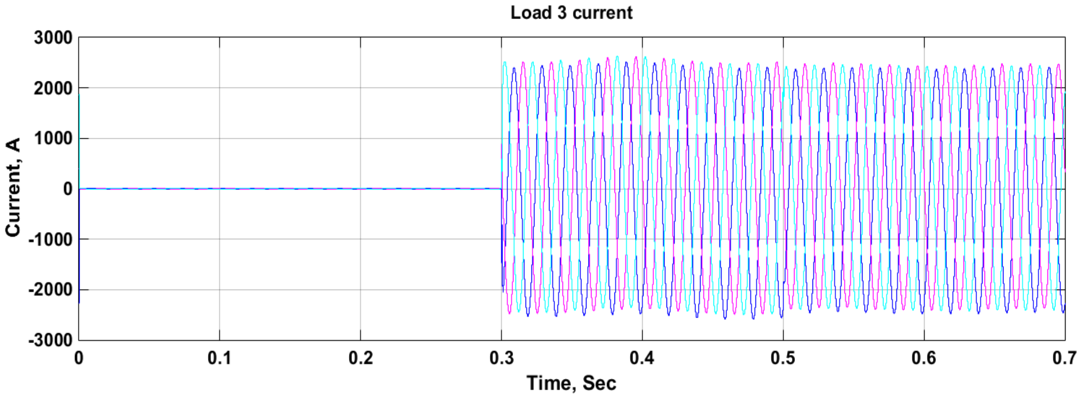

Figure 5.25 b. The instantaneous current across load 3.

Figure 5.25 c illustrates load 3 power. Load 3 is linked to the system from 0.3 sec to 0.7 sec as per load profile setting 1 (see Table 5.1).

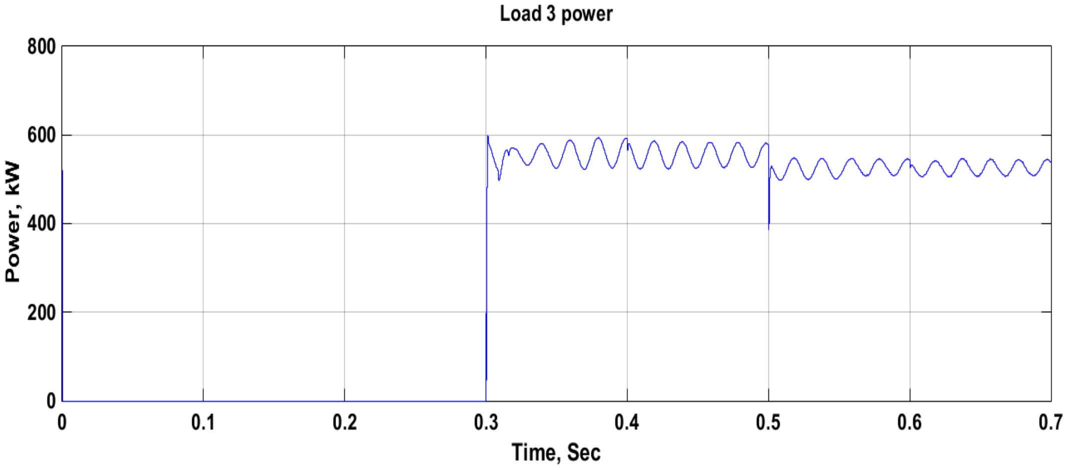

Figure 5.25 c. The actual power for loads 3.

Load Profile Setting 2:

It contains three case studies

Case Study A (Performance of the Suggested MAS)

The following figures illustrate the performance of the suggested MAS**.** Figure 5.26 illustrates load profile setting 2 of the system according to Table 5.3.

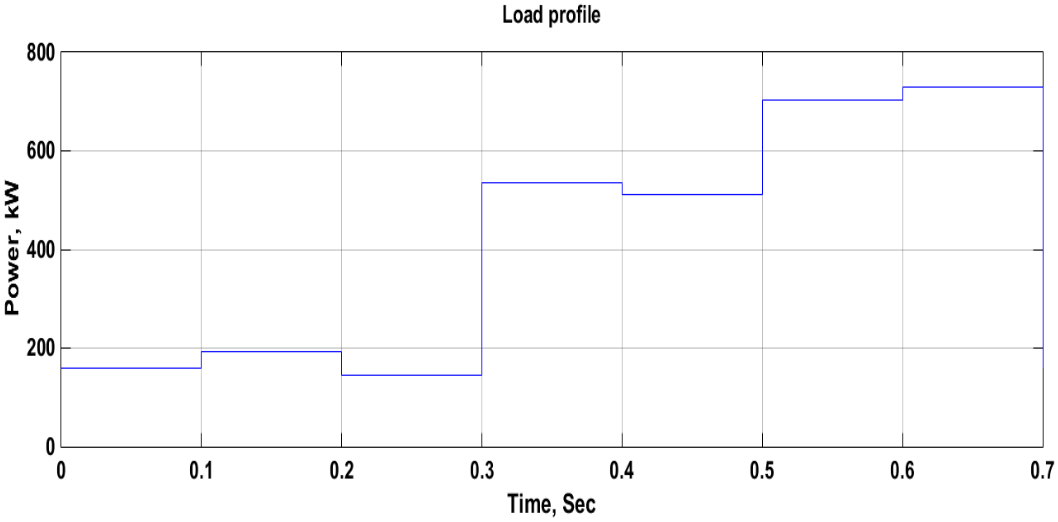

Figure 5.26. Load profile setting 2 of the system.

Table 5.4. Load profile setting 2.

TIME (sec)	LOAD1 (kW)	LOAD2 (kW)	LOAD3 (kW)	TOTAL (kW)
0-0.1	10	50	100	160
0.1-0.2	12	40	150	202
0.2-0.3	5	100	40	145
0.3-0.4	15	120	400	535
0.4-0.5	17	195	300	512
0.5-0.6	13	190	500	703
0.6-0.7	9	170	550	729

Figure 5.27 illustrates the actual load power 2 of the system.

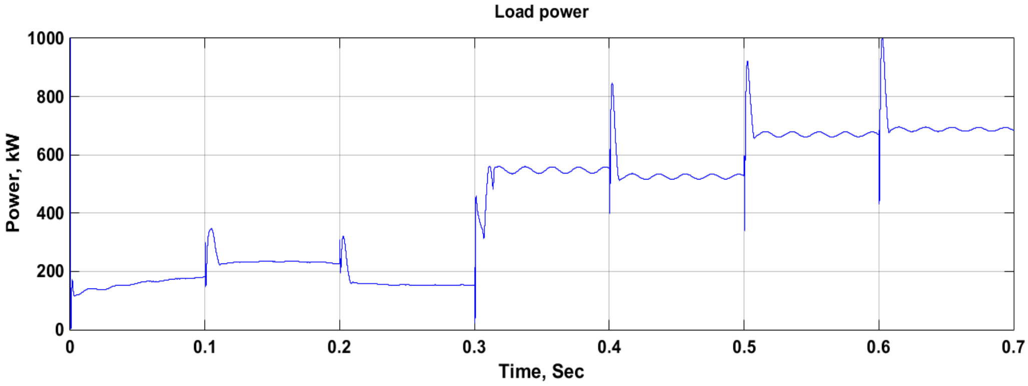

Figure 5.27. Load power 2 of the system.

Figure 5.28 illustrates power generation 2 of the system.

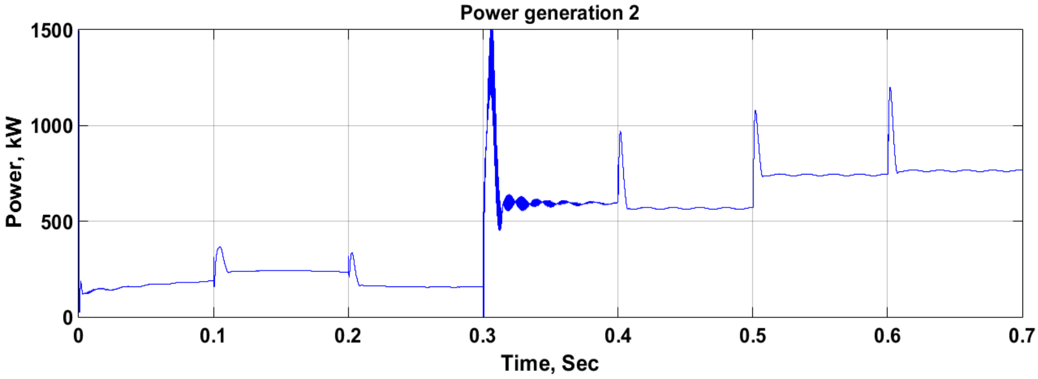

Figure 5.28. Power generation 2 of the system.

Figure 5.29 illustrates balance power 2 of the system.

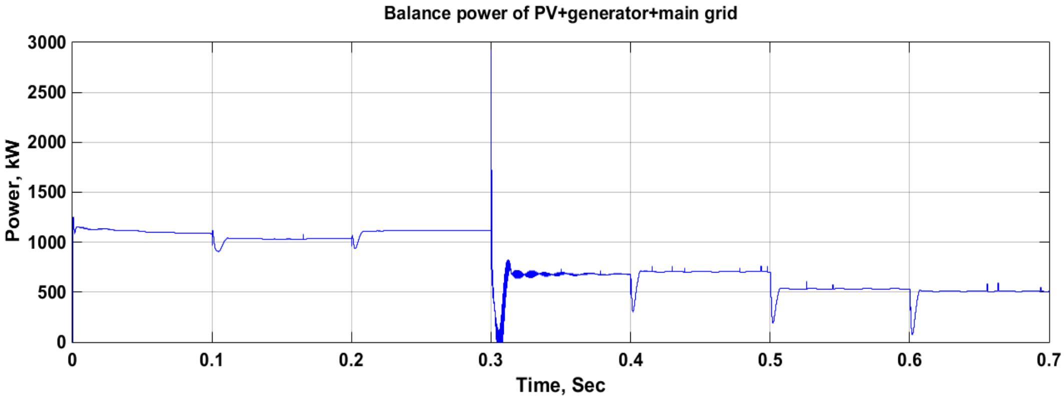

Figure 5.29. Balance power 2 of the system “PV – generator – main grid”.

Figure 5.30 illustrates the efficiency 2 of the system “PV – generator – main grid”.

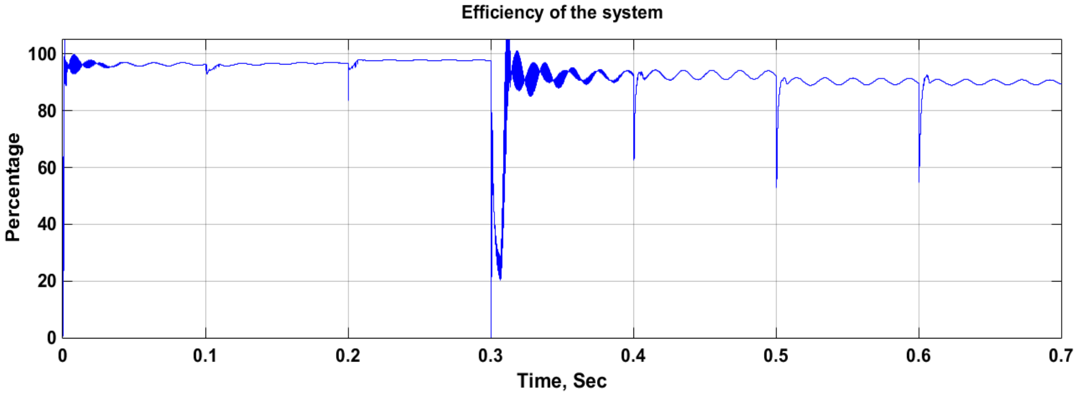

Figure 5.30. Efficiency 2 of the system “PV – generator – main grid”.

Case Study B (Control Signals of the Suggested MAS)

This case study contains control signals of PV, generator and main grid. Figure 5.31 shows the PV ON/OFF statuses. In the period from 0-0.3 sec all loads are fully supplied from PV panels and generator.

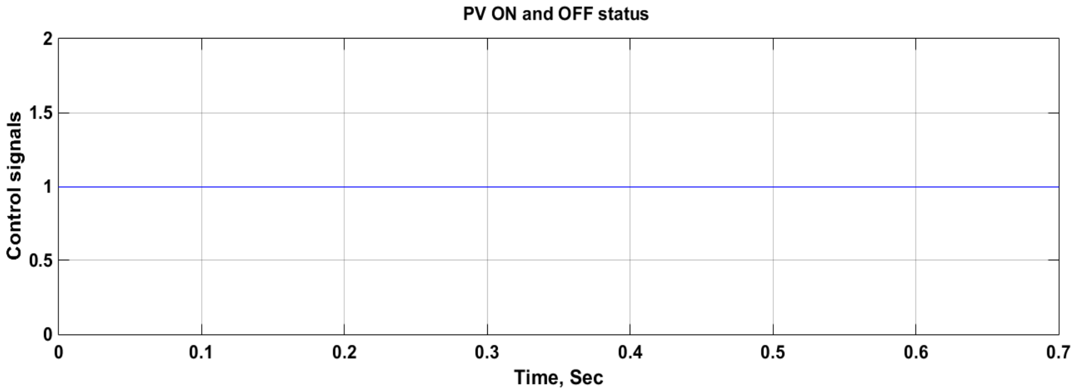

Figure 5.31. Control signals 2 of PV panels.

Figure 5.32 shows the generator ON/OFF statuses. The generator is turn-on just in the period from 0-0.3 sec.

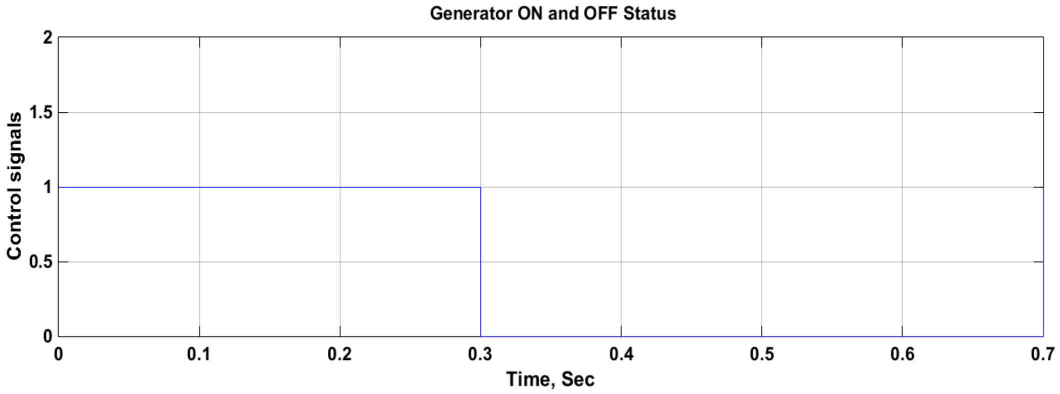

Figure 5.32. Control signals 2 of the generator.

Figure 5.33 shows the main grid ON/OFF statuses. The system is in the grid-connected mode in the period from 0.3-0.7 sec.

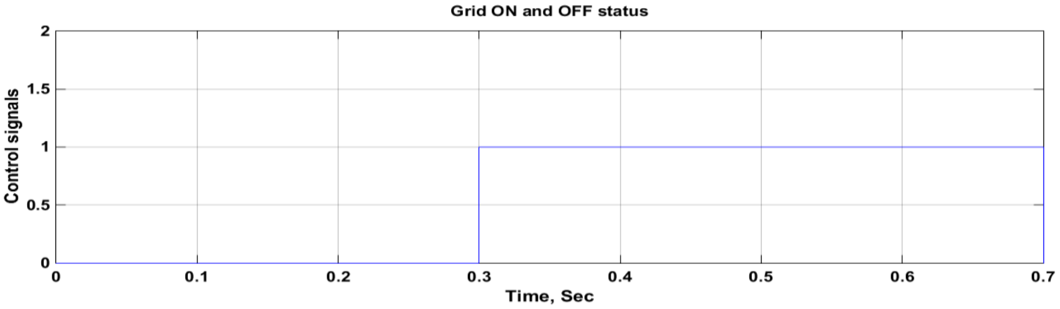

Figure 5.33. Control signals 2 of the main grid.

From case studies A and B, we can conclude Table 5.5 as represented below:

Table 5.5. Microgrid operation modes during different dynamical loads.

TIME (sec)	0-0.1	0.1-0.2	0.2-0.3	0.3-0.4	0.4-0.5	0.5-0.6	0.6-0.7
LOAD (kW)	160	202	145	535	512	703	729
OPERATION MODES	Island mode	Island mode	Island mode	Grid mode	Grid mode	Grid mode	Grid mode

Time 0-0.1 sec:

During this time load profile setting is 160 kW, actual load power is around 155 kW, power generation is around 161 kW, the efficiency of the system is 96.2% and the connection is in an island mode. The control signals for PV panels and generator are one and the control signal for the CB of the main grid is zero. The total load is 160 kW, the PV panels and the generator can supply up to 424 kW and no need to purchase power from the main grid that’s why the system is in an island mode.

Time 0.1-0.2 sec:

During this time load profile setting is 202 kW, actual load power is around 229 kW, power generation is around 236.5 kW, the efficiency of the system is 96.8% and the connection is in an island mode. The control signals for generator and PV panels are one and the control signal for the CB of the main grid is zero. The total load is 202 kW, the PV panels and the generator can supply up to 424 kW and no need for purchasing electrical power from the main grid.

Time 0.2-0.3 sec:

During this time load profile setting is 145 kW, actual load power is around 152 kW, power generation is around 156 kW, the efficiency of the system is 97.4% and the connection is in an island mode. The control signals for generator and PV panels are one and the control signal for the CB of the main grid is zero. The total load is 145 kW, the PV panels and the generator can supply up to 424 kW and no need for buying electrical power from the main grid.

Time 0.3-0.4 sec:

During this time load profile setting is 535 kW, actual load power is around 558 kW, power generation is around 605 kW, the efficiency of the system is 92.2% and the connection is in a grid-connected mode. The control signals for PV panels and the main grid circuit breaker are one and the control signal for the circuit breaker of the generator is zero. The total load is 535 kW, the PV panels and generator can supply up to 424 kW but the current load is 550 kW so the PV panels and the main grid will supply the power to the load and the generator is in shut off condition.

Time 0.4-0.5 sec:

During this time load profile setting is 512 kW, actual load power is around 536 kW, power generation is around 572 kW, the efficiency of the system is 93.7% and the connection is in a grid-connected mode. The control signals for the PV panels and main grid are one and the control signal for the circuit breaker of the generator is zero. The total load is 512 kW, the PV panels and the generator can supply up to 424 kW but the current load is 567 kW so the PV panels and the main grid will supply the power to the load and the generator is in shut off condition.

Time 0.5-0.6 sec:

During this time load profile setting is 703 kW, actual load power is around 720 kW, power generation is around 743 kW, the efficiency of the system is 96.9% and the connection is in a grid-connected mode. The control signals for PV panels and the main grid are one and the control signal for the circuit breaker of the generator is zero. The total load is 703 kW, the PV panels and the generator can supply up to 424 kW but the current load is 703 kW so the PV panels and the main grid will supply the power to the load and the generator is in shut off condition.

Time 0.6-0.7 sec:

During this time load profile setting is 729 kW, actual load power is around 735 kW, power generation is around 790 kW, the efficiency of the system is 93% and the connection is in a grid-connected mode. The control signals for PV panels and the main grid are one and the control signal for the generator is zero. The total load is 729 kW, the PV panels and the generator can supply up to 424 kW but the current load is 729 kW so the PV panels and the main grid will supply the power to the load and the generator is in shut off condition.

Case Study C (Loads Windows)

Load 1 Window:

It contains the instantaneous voltage 2 across load 1, the instantaneous current 2 through load 1 and the actual power 2 for load 1. Figure 5.34 a illustrates the instantaneous voltage 2 across load 1.

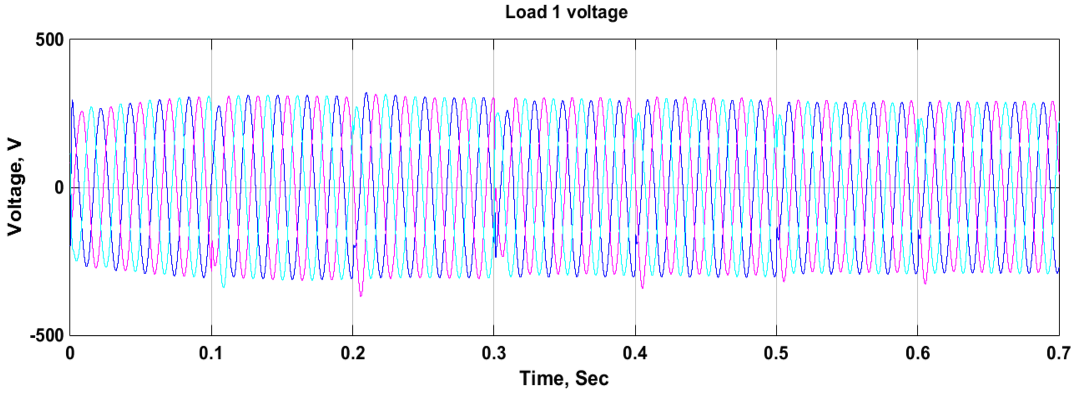

Figure 5.34 a. The instantaneous voltage 2 across load 1.

Figure 5.34 b illustrates the instantaneous current 2 through load 1.

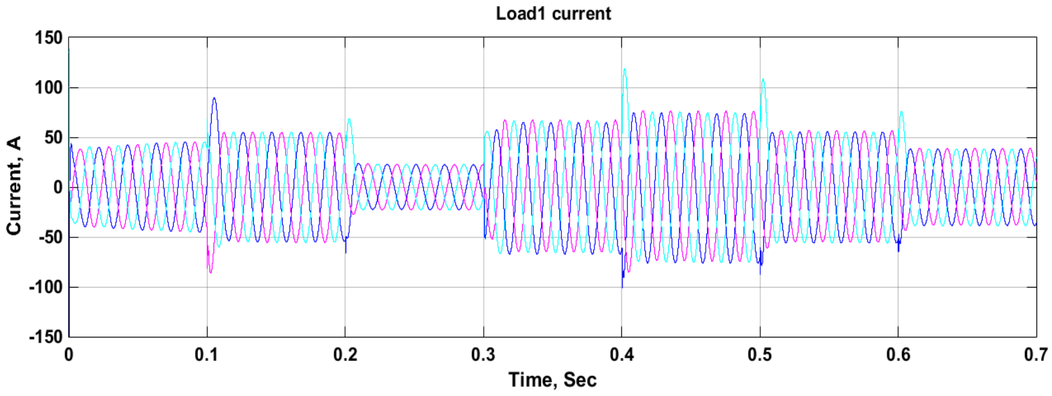

Figure 5.34 b. The instantaneous current 2 through load 1.

Figure 5.35 c illustrates the actual power 2 for load 1. Load 1 is linked to the system from 0 sec to 0.7 sec as per load profile setting 2 in Table 5.2.

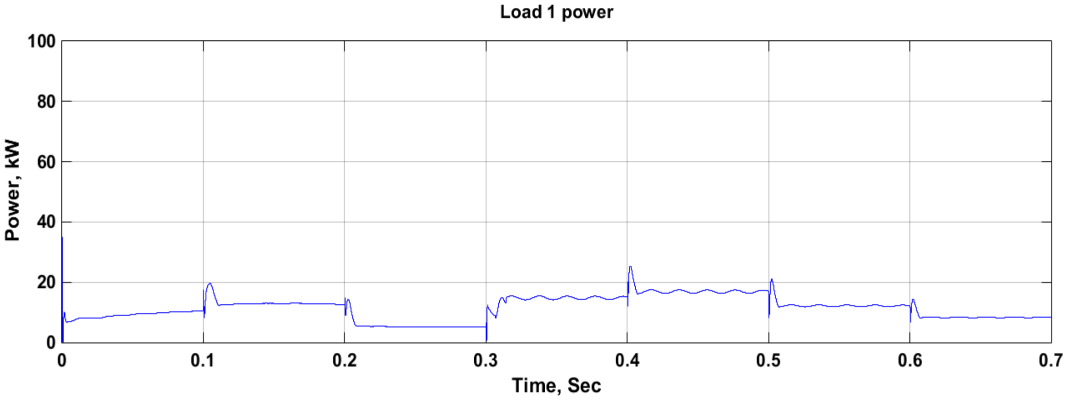

Figure 5.34 c. The actual power 2 for load 1.

Load 2 Window:

It contains the instantaneous voltage 2 across load 2, the instantaneous current 2 through load 2 and the actual power 2 for load 2. Figure 5.35 a illustrates the instantaneous voltage 2 across load 2.

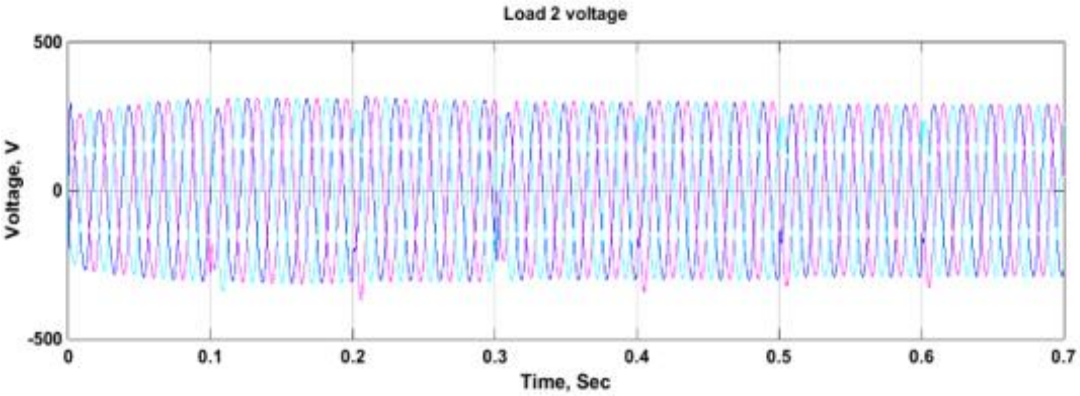

Figure 5.35 a. The instantaneous voltage 2 across load 2.

Figure 5.35 b illustrates the instantaneous current 2 through load 2.

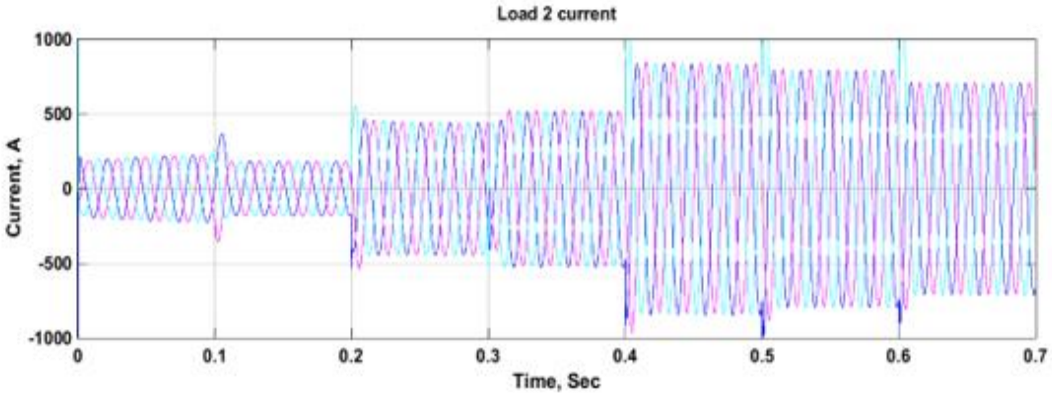

Figure 5.35 b. The instantaneous current 2 through load 2.

Figure 5.35 c illustrates the actual power 2 for load 2. Load 2 is connected to the system from 0 sec to 0.7 sec as per load profile setting 2 in Table 5.2.

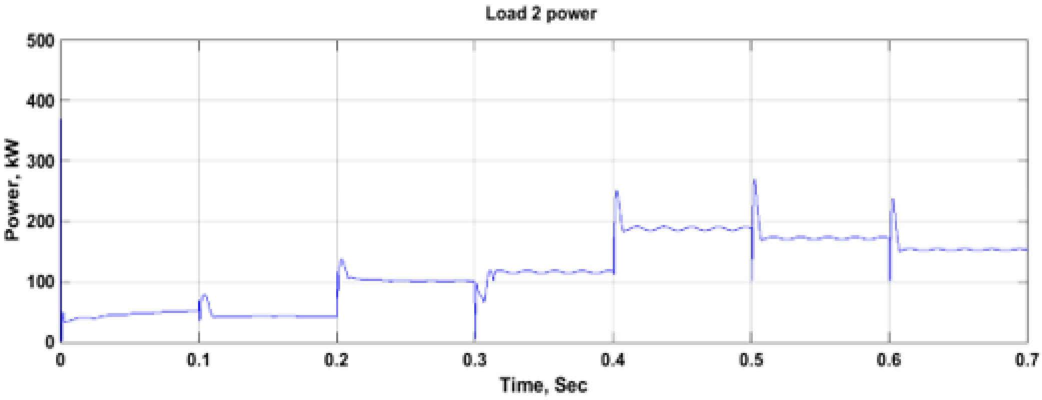

Figure 5.35 c. The actual power 2 for load 2.

Load 3 Window:

It contains the instantaneous voltage 2 across load 3, the instantaneous current 2 through load 3 and the actual power 2 for load 3. Figure 5.36 a illustrates the instantaneous voltage 2 across load 3.

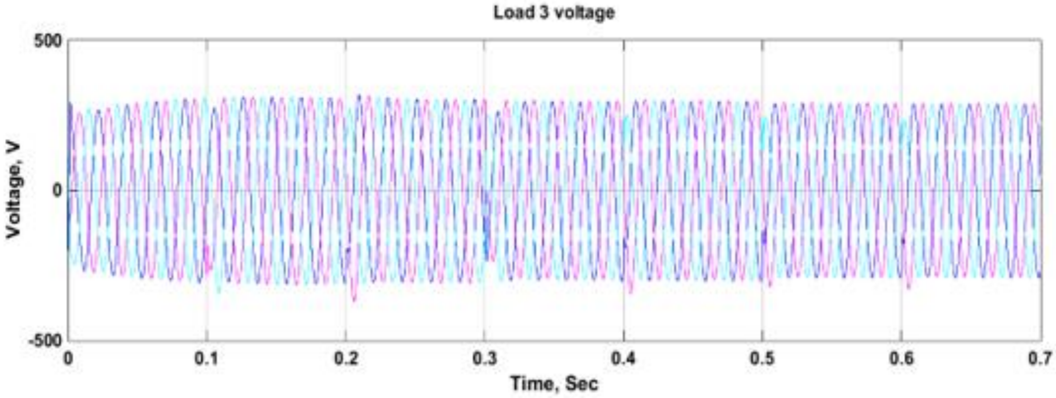

Figure 5.36 a. The instantaneous voltage 2 across load 3.

Figure 5.36 b illustrates the instantaneous current 2 through load 3.

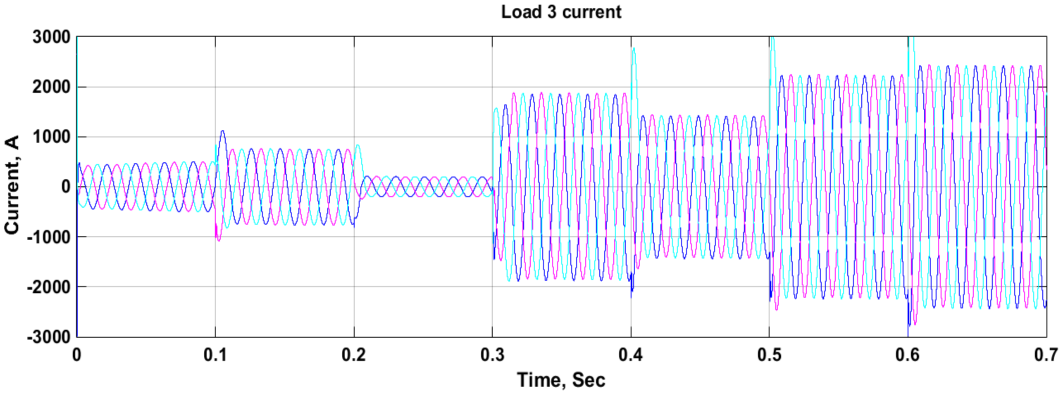

Figure 5.36 b. The instantaneous current 2 through load 3.

Figure 5.36 c illustrates the actual power 2 for load 3. Load 3 is linked to the system from 0 sec to 0.7 sec as per load profile setting 2 in Table 5.2.

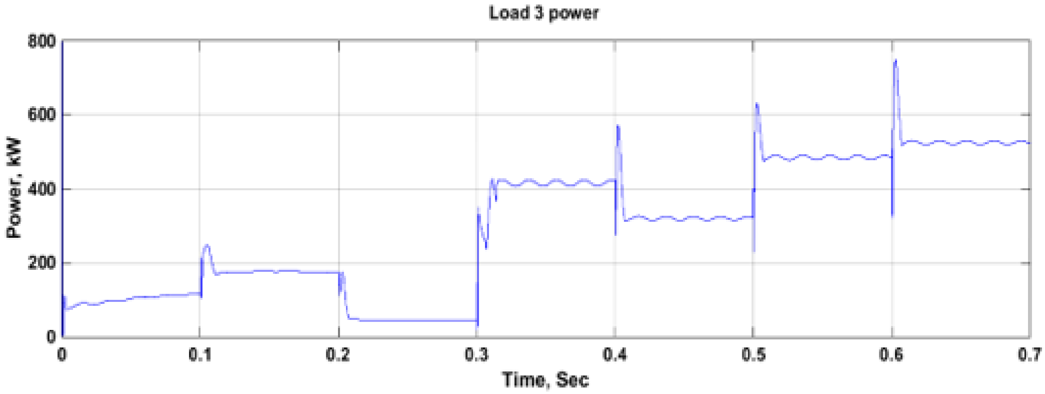

Figure 5.36 c. The actual power 2 for load 3.

PART 6

CONCLUSION

This work studies a decentralized agent-based approach to microgrids management and how it can contribute to meet the increasing needs of the new electricity sector. It also discusses applications of MASs in microgrids and how to apply the suggested approaches to include different sides of energy system operations and the practical effects of implementing such approaches.

Following standard design techniques and agent communication protocols, a MAS was developed for a microgrid containing three agents: control agent, DER agent, and load agent. The MAS executes an algorithm to support tasks of transformation from grid-connected mode to an island mode seamlessly in the event of detecting main grid failure, protecting critical loads, implementing load shedding for non-critical loads and service restoration to grid-connected mode as soon as the main grid voltage attains to the allowable value.

Also, in light of the distributed nature of microgrid, the multi-agent system offers an appropriate intelligent interface for the microgrid. The task of this interface is to assure the power balance among the demand for power and power supply (generated power) with maximum efficiency and reduce fuel cost during operation modes of the microgrid. In this context, a management algorithm based on agent’s negotiations has been implemented. A MAS has been developed which contains four agents control agent, power generation agent, load agent and monitoring agent to manage and control the power flow from and to the microgrid. These agents can interact and take appropriate decisions depending on the information exchanged by messages between them.

The proposed MAS has been developed in the JADE platform for manage and control a MG simulated in MATLAB/Simulink. Multi agent control simulation JADE extension (MACSimJX) toolkit as an interface has been used to exchange data among MG in MATLAB/Simulink and MAS in the JADE platform.

The simulation outcomes show that suggested MASs promote the transition seamlessly from grid-connected mode to an island mode when the main grid failure is revealed, protecting critical loads, executing load shedding for non-critical loads and service restoration. The simulation results also demonstrate the capability of the MAS to make a power balance between demand for power and supply with maximum efficiency and reduce fuel cost in two microgrid operation modes during different dynamical loads.

6.1. CONTRIBUTIONS OF THESIS

In this study, MACSimJX as a middleware was proposed to connect the MAS developed in the JADE platform to a MG designed in MATLAB / Simulink. Moreover, the development and design of assignable agents for microgrid applications were also examined. In order to test the interaction, coordination, and behavior of agents under various statuses, the agents have been placed in a simulated microgrid environment where different case studies have been performed.

The most important goal of this thesis is to implement the applications of MASs in a MG based on the messages exchanged between agents. This thesis demonstrates the ability of agents to control and coordinate microgrid operations in a simulated real-time environment. Different dynamic loads have been simulated for each time interval. Additionally, the developed MAS acts in compliance with the specifications of the FIPA which offer the essential needed standards for Agent design and development. Agents created under this suggested framework are employed to implement particular tasks so as to increase the advantages in the context of MGs. Specifically, these involve control algorithms for limited power supply management from distributed energy resource that are available to keep critical loads during emergency cases, while load shedding is performed for non-critical loads and service restoration when the system voltage attains to the allowable value. In addition, maximize the economic benefits of the microgrid. This study is expected to submit an insight into the development and design of a MAS, in addition, the base for experimental applications of an agent-based technology in a MG environment.

6.2. RECOMMENDATIONS

The following suggestions submit future works on research and development that may give new insights into the applications of a MAS in microgrids operation.

- Discussing and assessing simulation results in this work serves as a first step towards the development and hardware implementation of distributed agent-based management for operation of the MG effectively. The proposed MAS-based model for decentralized microgrid management requires more tryouts through an actual experimental setup study and valuation.
- For better storage of energy, additional DERs and storage units could be integrated into the system. The obtainable power could be stocked for later utilization when the power demand is low.
- Integrating more DERs require more search for determining new functions for a DER agent.
- To assess the long-term extensibility of the multi-agent system, the impact of expanding number for agents on the stability of control units can be considered.
- With existing many DERs to provide power for MGs, a competitive power market can be established.

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APPENDIX A.

RESEARCH OBJECTIVE SPECIFICATIONS

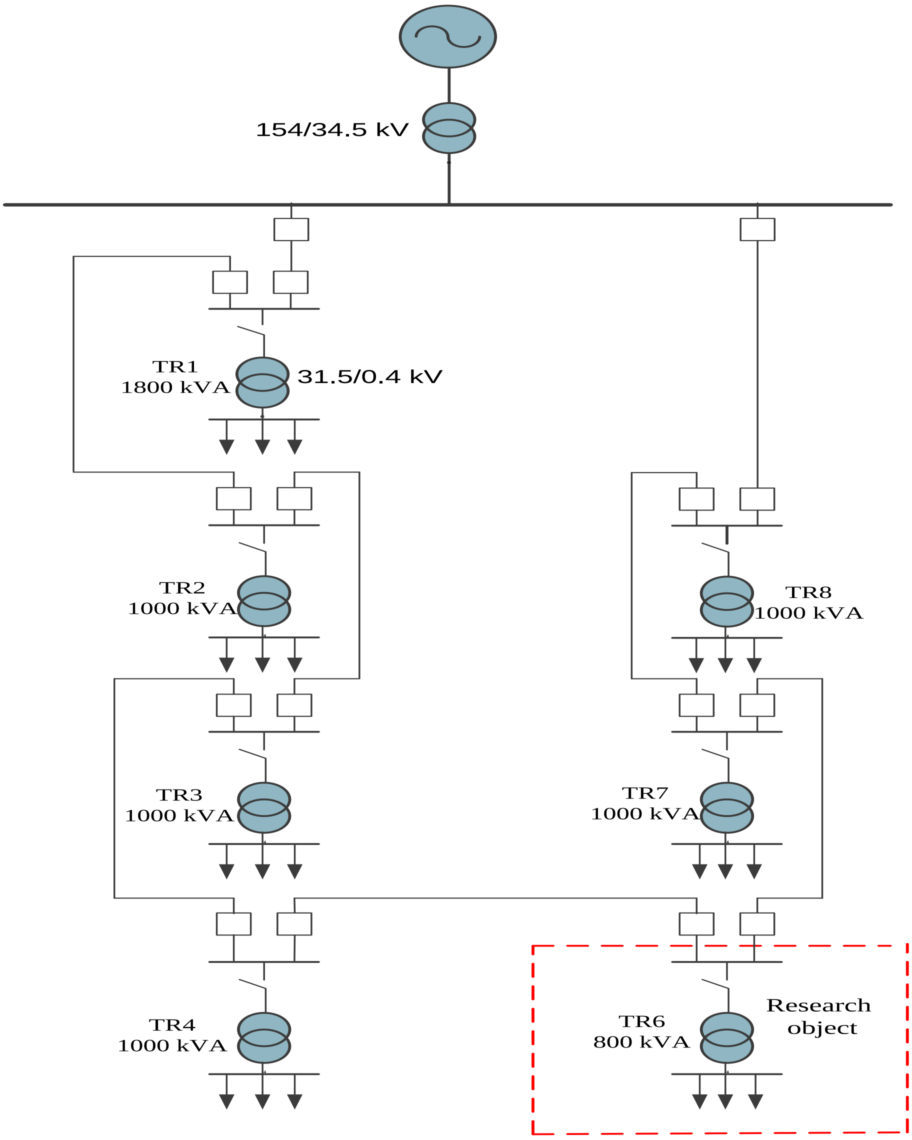

Figure Appendix A.1. Scheme distribution of electrical power for Karabuk University.

Table Appendix A.1. Specifications of transformer in the substation of KBU.

TRANSFORMER POWER	75 MVA
PRIMARY VOLTAGE OF TRANSFORMER	154 kV
SECONDARY VOLTAGE OF TRANSFORMER	34.5 kV
POWER OF SHORT CIRCUIT	7256 MVA
PER UNIT SHORT CIRCUIT VOLTAGE, %	11.33
RELATIVE OHMIC SHORT CIRCUIT VOLTAGE, %	0.7
RATED VOLTAGE	34.5 kV

Table Appendix A.2. Specifications of Karabuk University distribution center transformer (TR6).

POWER OF TRANSFORMER	7600 MVA
VOLTAGE OF PRIMARY COIL OF TRANSFORMER	34.5 kV
VOLTAGE OF SECONDARY COIL OF TRANSFORMER	0.4 kV
PER UNIT SCV, %	3.9
LOSS OF COPPER	8 kW
RATED VOLTAGE	0.4 kV

Table Appendix A.3. PV cell FLM-310P-72 specifications.

OUTPUT POWER, W	291	294	301	351	311
VOLTAGE AT PMAX , V	37.17	37.55	38.06	37.35	37.48
CURRENT AT PMAX, A	7.80	7.83	7.85	7.99	8.05
VOLTAGE AT OPEN-CIRCUIT, V	43.84	43.92	44.10	44.30	45.49
CURRENT AT SHORT-CIRCUIT, A	8.3	8.45	8.47	8.50	8.58

Table Appendix A.4. Thermal characteristics of PV cell FLM-310P-72.

RATED OPERATING TEMPERATURE OF CELL	NOCT	℃	45±2
PMAX TEMPERATURE COEFFICIENT		%/ ℃	-0.45
VOC TEMPERATURE COEFFICIENT	β_{Voc}	%/ ℃	-0.34
ISC TEMPERATURE COEFFICIENT	α_{Isc}	%/ ℃	0.06
VMPP TEMPERATURE COEFFICIENT	β_{Vmpp}	%/ ℃	-0.40

Table Appendix A.5. Xtender XTM 3500-24 inverter specifications.

RATE VOLTAGE OF BATTERY	24 Vdc
RANGE OF INPUT VOLTAGE	19 – 34 Vdc
CONTINUOUS POWER @ 25℃	3000 VA
POWER 30 MIN. @ 25℃	3500 VA
POWER 5 SEC. @ 25 ℃	9 KV/A
MAXIMUM LOAD	U_p to short- circuit
MAXIMUM ASYMMETRIC LOAD	U_p to P_{cont}
LOAD DETECTION (STAND-BY)	2 to 25 W
COS ϑ	0.1-1
MAXIMUM EFFICIENCY	94%
CONSUMPTION OFF/STAND-BY/ON	1.4W/1.6W/12W
OUTPUT VOLTAGE	Pure sine wave 230Vac $(\pm 2\%)/120$ Vac
OUTPUT FREQUENCY	Adjustable 45 – 60 Hz $\pm 0.05\%$
DISTORTION OF HARMONIC	$< 2\%$
SHORT AND OVERLOAD- PROTECTION OF CIRCUIT	Automatic disconnection with 3-time restart attempt
PROTECTION FROM OVERHEAT	Warning before shut- with-off – with automatic restart
CHARACTERISTIC OF CHARGE	6 steps: bulk – absorption – floating – equalization – reduced floating – periodic, absorption
MAX CURRENT OF CHARGING	90 A
COMPENSATION OF TEMPERATURE	With BTS-01 or BSP500/1200
POWER FACTOR CORRECTION (PFC)	EN 61000-3-2
RANGE OF INPUT VOLTAGE	150 to 265Vac /50 to 140Vac
FREQUENCY OF INPUT	45 to 65 Hz
MAX INPUT CURRENT. (TRANSFER RELAY)/ MAX OUTPUT CURRENT.	50Aac /56Aac
TIME OF TRANSFER	$< 15\ ms$
CONTACTS OF MULTIFUNCTION	2 independent contacts (potential free 3 points, 16A–250Vac /3–50 Vdc
WEIGHING	21.2 Kg
DISTANCES H/W/L[MM]	133/322/466
INDEX OF PROTECTION	IP20
RANGE OF OPERATING TEMPERATURE	-20 to 55℃
RELATIVE HUMIDITY DURING OPERATION	95 % without condensation
VENTILATION	Enforced from 55℃
SCALE ACOUSTIC	$< 40\ dB/< 45dB(without/with$ ventilation)
CERTIFICATION OF ISO	9001:2008/14001:2004

Table Appendix A.6. Discharge current at V=1.83 V/cell of battery MUTLU 6OPzS-300.

15 min	**30 min**	**1 hour**	**2 hours**	**3 hours**	**4 hours**	**5 hours**	**6 hours**	**8 hours**	**10 hours**
184	157	123	88.7	67	56.6	47	42.1	34.6	28.6

Table Appendix A.7. Discharge current at V=1.80 V/cell of battery MUTLU 6OPzS-300.

15 min	**30 min**	**1 hour**	**2 hours**	**3 hours**	**4 hours**	**5 hours**	**6 hours**	**8 hours**	**10 hours**
217	181	145	91	72	56	43	43.3	37	31

Table Appendix A.8. Discharge current at V=1.75 V/cell of battery MUTLU 6OPzS-300.

15 min	**30 min**	**1 hour**	**2 hours**	**3 hours**	**4 hours**	**5 hours**	**6 hours**	**8 hours**	**10 hours**
221	206	154	101	75	61	53.8	45	36.6	32

Table Appendix A.9. Discharge current at V=1.70 V/cell of battery MUTLU 6OPzS-300.

15 min	**30 min**	**1 hour**	**2 hours**	**3 hours**	**4 hours**	**5 hours**	**6 hours**	**8 hours**	**10 hours**
288	226	161	104	78	65	56	46	38	32.2

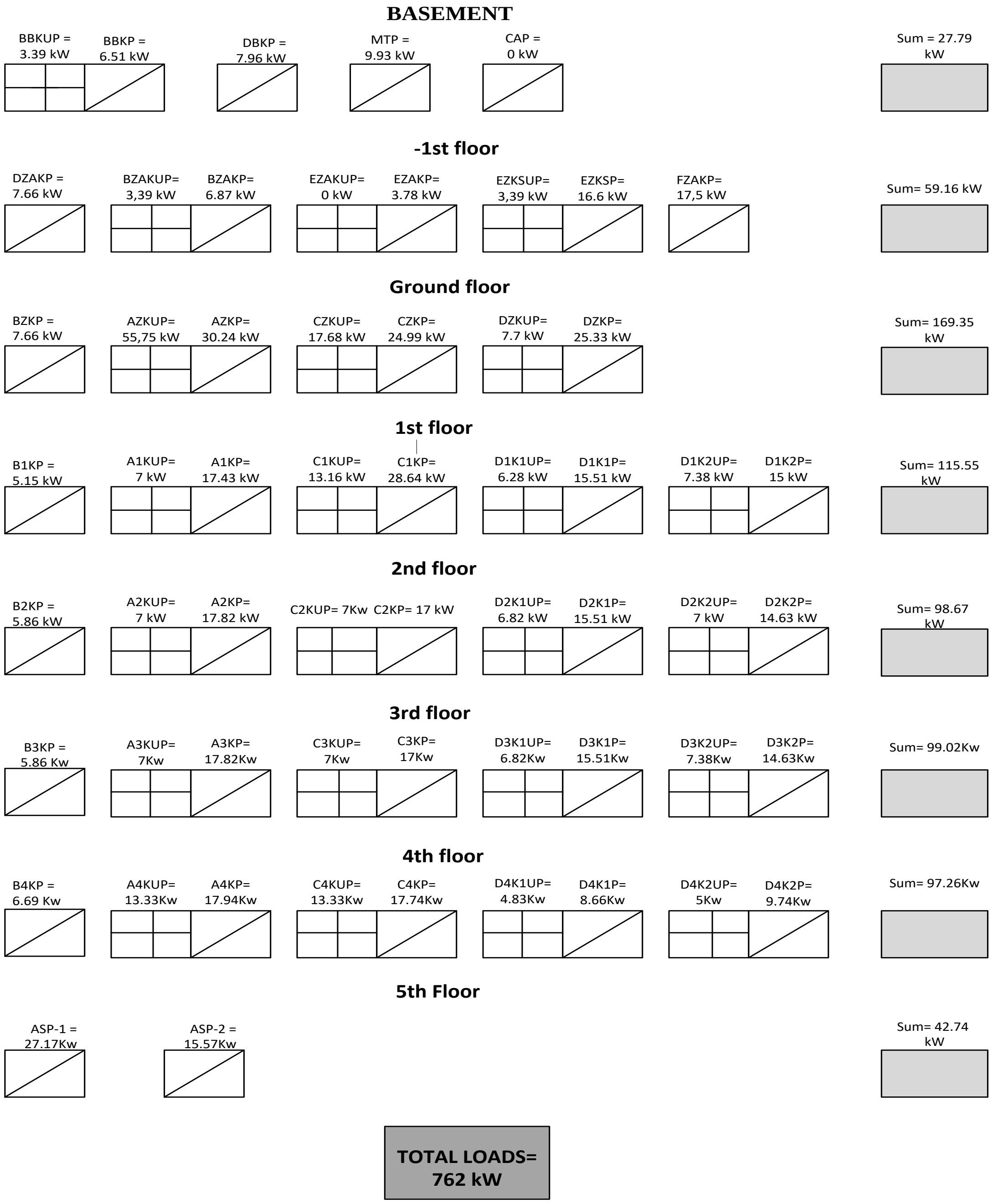

Figure Appendix A.2. Scheme of TR-6 structure loads distribution.

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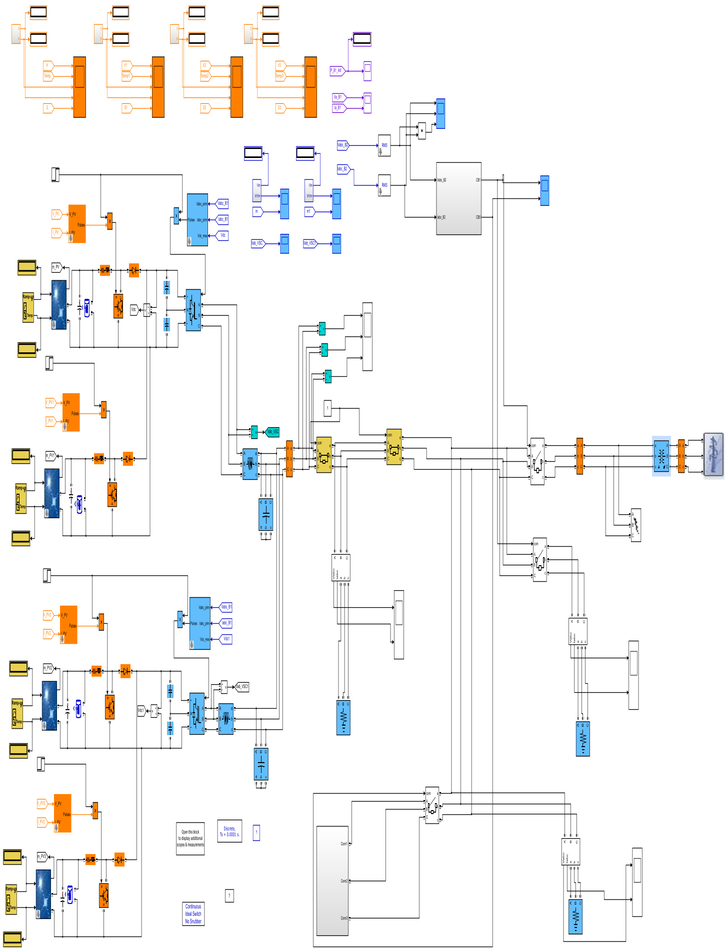

Figure Appendix A.3. Microgrid model in MATLAB/Simulink.

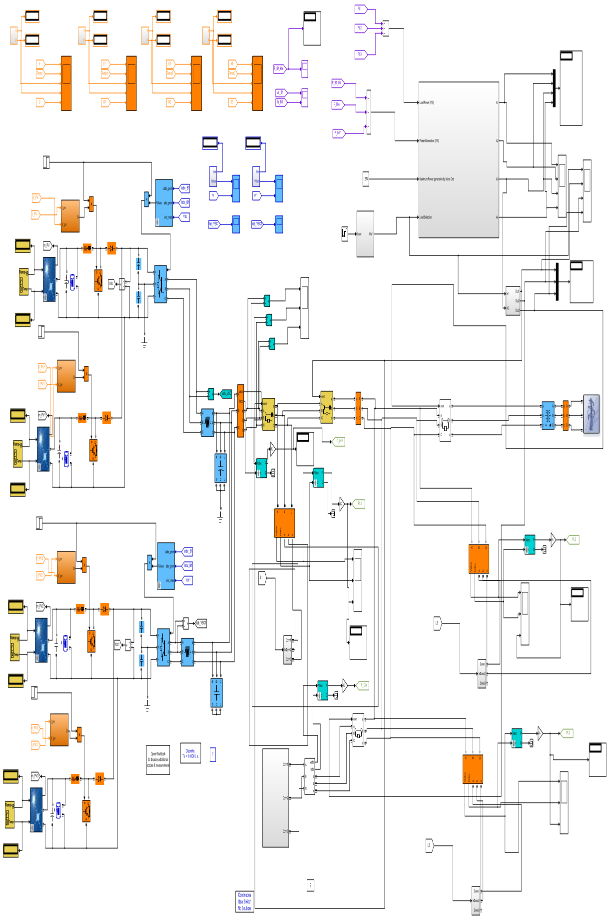

Figure Appendix A.4. A testbed simulated in MATLAB/Simulink.

APPENDIX B.

PUBLISHED PAPERS

ESCI-indexed Journal

1. Anis, I., and Yusupov, Z., “Development of a Mas Based Distributed Intelligent Control and Fault Control Strategy for Microgrid”, ***Politeknik Dergisi***, Gazi University Publication, (2020)
2. Anis, I., Yusupov, Z., and Nuri, A., “Development of a MAS Based Distributed Intelligent Control Strategy for Microgrid”, ***Ciencia e Tecnica Vitivinicola***, Dios Portos, Portugal Publication, (2019)

CONFERENCES

1. Anis, I., and Yusupov, Z., “Applications of multi-agent systems in microgrid control”, ***ICAT Conference on Advanced Technology and Sciences,*** (2017)

RESUME

ANIS SULAYMAN AMHARIB ISSA was born in Benghazi in 1982 and graduated primary and preparatory education from Shahat city. He finished secondary school education in Aloroba High School, after that he finished the undergraduate program in Omar al mukhtar University department of Electrical and Electronics in 2003. In 2012 he graduated Master of Science in the Electrical and Electronics department at Tripoli University. In 2015 he started in the Ph.D. program in the Electrical and Electronics department of Karabuk University and he has been still working in Ph.D. program until now.

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